ON-LINE CONTROL OF WORKPIECE DIMENSION IN TURNING OPERATION

by

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CERTIFICATE

This is to certify that the thesis entitled, "ON-LINE CONTROL OF WORKPIECE DIMENSION IN TURNING OPERATION" by Ramesh, S., Roll No. 8720522, is a record of work carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Tool wear is one of the major factors for limiting the performance of the machine tool. It affects the dimensional accuracy of the workpiece as well as the tool life.

Present work deals with the development of a feedback control system to on-line monitor the tool wear and provide compensation for the tool wear to keep the dimension of the workpiece within tolerance limits.

In this thesis an attempt has been made to use an optical displacement sensor as an on-line-tool-monitoring devices. The sensor consists of an ordinary bulb as a light source, bifurcated optical fibres for transmitting light to and from the workpiece surface and a phototransistor. The sensor was mounted in line with the tool, on the other side of the workpiece.

The positioning of the tool was performed by rotating the cross-feed screw by a stepper motor. A microprocessor kit was used as a controller.

The magnitude of the width of flank wear land was further measured with the help of a shadow-graph and was compared with the one obtained from the sensor output. The principle, verified by the experimental results, indicates the accuracy of wear measurement and compensation for different cutting conditions.

CHAPTER-1

INTRODUCTION

1.1 Introduction

An Adaptive System [2] measures a certain index of performance (IP) using the inputs, the states and the outputs of the adjustable system. From the comparison of the measured index of performance and a set of given ones, the adaptation mechanism modifies the parameters of the adjustable system or generates an auxiliary input in order to maintain the IP close to the given set of value.

For the purposes of this work on machining, adaptive control is particularly defined as a feedback system that allows to detect a changing environment (e.g. tool wear, variation in work material hardness, cutting forces, etc.) and then to take adaptive actions (change the machining conditions namely speed, and feed) to eliminate or compensate the change in process parameters.

This involves a feedback contour comprising (a) sensing, (b) decision making and (c) adjusting the inputs.

The Adaptive control system for machine tools are classified [13] into two groups namely, (a) ACO - Adaptive control optimization in which the machining conditions are

optimized within the prescribed limits of machine and tool constraints such as maximum torque, force, etc.

A closed-loop adaptive control system needs sensors to detect the real state of the working environment. This information is crucial to the success of an adaptive control system, especially in the cases of time varying situations.

In any production process, ACO will be the ultimate goal. Its implementation to the machining operations requires the on-line monitoring of the machining condition and sensors for measuring tool wear rate.

Tool wear will occur due to many reasons namely,abrasion, adhesion and diffusion. Predominately two types of tool wear have been identified.

The crater wear is formed on the rake face of the tool due to the diffusion. The flank wear is formed on the flank face which always rubs against the machined surface. Due to the increase in flank width, the dimension of the workpiece will vary. The flank wear causes more area of contact with the workpiece which results in increase in cutting forces, cutting temperature and machine tool chatter, ultimately resulting in tool failure. The tool wear rate will be higher in machining hard alloys like, High carbon steels, EN - steels, Stainless steels and Titanium alloys.

Therefore, it is very much necessary to monitor the tool wear and control the workpiece dimensions by Adaptive mechanisms.

Also, on-line monitoring of all the parameters which vary the cutting process such as force and chatter and having a combination of ACO and ACC is very much desirable for achieving economic requirements including the improvements in tool life.

Good amount of research work has been done in recent past in the field of on-line monitoring of tool wear. They can be classified into two groups namely (a) Direct tool wear sensing and (b) Indirect tool wear sensing.

Direct tool wear sensing implies that the actual progress of the tool wear is sensed during the cutting process. This includes such methods as Radioactive [19,20], optical [9,10], pneumatic [20], electrical resistance [21] etc.

Indirect tool wear sensing relies on monitoring other variables on the process. These other variables are fairly correlated to the progression of wear and are presumably easy to sense.

Such methods include monitoring the change in workpiece dimensions [14, 17], vibration (frequency band energy method) [16], acoustic emission method [22], cutting temperature [20], surface morphology, [18,23], cutting forces [15] etc. Out of all the above mentioned methods, it is found that optical methods [8,10] give best sensitivity, accuracy and reliability.

In the following section a detailed review of relevant works carried out in the fields of adaptive control and optical methods for monitoring the machining zone are presented.

1.2 Literature Survey

A great amount of research has been done in ACO as well as ACC since 1960. Yorem Koren and Joseph Ben-uri [13] state that ACO cannot be successfully applied practically due to the non-availability of reliable and accurate tool wear sensors. According to them ACC is much easily applicable to practical conditions.

Even in ACC most of the works carried out is on the limitations of cutting forces.

Oren Masory and Yorem Koren [1] have dealt with the control system which has a dynamometer acting as a force sensor. The feed is altered in proportion to the error signal which is the discrepancy between the set value and measured value of the feed force. The whole experiment is carried on a CNC lathe with a variable depth of cut, with the aim to keep feed force constant.

D.W. Yen and P.K. Wright [2] have proposed an optimization procedure for adaptive control based on the physical constraints of the machining procedure. They have identified three modes of tool failure namely plastic deformation, cratering and fracture at high cutting speeds and feeds. They have examined these failures and arrived at the constrained units for each mode of failure. Using these constraints the cutting conditions have been optimized based on the chosen performance index (material removal rate). The whole idea is a theoretical

approach. Effect on dimensional accuracy of the workpiece, surface finish and tool life have not been dealt with.

R. Mochinnon, G.E. Wilson [3] have carried out experiments on CNC Turret lathe using ACC. The various strategies are limit on spindle power per unit depth of cut to prevent premature tool failure, air-cutting to ensure safe entry into metal while minimising air-cutting time, feed limitation to ensure chip-breaking and to avoid excessive force and torque during the transient period. It has been concluded that realization of the first and third strategies depends entirely on the reliability of tool wear and force sensors.

O. Masory and Y. Koren [4] have dealt with the stability analysis of constant force ACC system thus making it possible to select appropriate gains which will maintain the stability of the system. They have verified this by conducting experiments on CNC lathe and determined a stability region for such a system.

L. Liu, N.K. Sinha and M.A. Elbestwi [5] have done a computer simulation of Geometric Adaptive Control for NC turning with the main objective of maintaining geometric accuracy of finished workpiece in presence of significant workpiece tool deflection error as well as random and periodic disturbances. They have suggested that the adaptive controller they have presented could be applied to any existing NC turning system if a suitable measuring system is available.

H.J. Jacobs, B. Hentschel and B. Stange [6] presented the idea of intelligent tool monitoring as the focus of process monitoring in a future-oriented concept of computer integrated manufacturing. They have proposed a self-optimizing adaptive control strategy for Machining cells using a cutting force sensor which also measures the tool wear.

M. Shiraishi, K. Uehara [7] have dealt with a non-contact measuring apparatus of workpiece dimension and in-process control, utilising the apparatus on a NC lathe. The measuring principle includes a laser unit, photoconductive cells and optical systems. The errors have been suppressed to within a tolerance limit of $\pm$ 10 μm. The errors in the dimension are corrected with positioning motors when the surface roughness exceeds the limit of $\pm$ 10 μm.

Slavo M. Arvoski [8] presents a survey of developed wear sensors for adaptive control systems of machine tools. Sensors based on pneumatic principle, capacitive principle, cutting resistance and optical principle have been discussed in detail. It has also been shown that optical principle has the best sensitivity, accuracy and reliability for measuring discontinuous tool wear. A new sensor based on the measurement of the radioactivity of activated cutting elements of the tool during cutting has been presented.

F. Giusti, M. Santochi, G. Tantussi [9] describe a method of on-line sensing of flank and crater wear of cutting

tools. They describe a sensor based on T.V. image analysis of worn tool. The flank wear is measured observing the active cutting part from a proper direction and lighting the wear land by a fibre optic system. The crater wear is visualised by lighting the tool by a laser system. From the obtained image it is possible to extract the position and dimensions of the crater and a complete mapping. By means of these systems the parameters of tool wear and tool wear morphology have been evaluated.

M. Shiraishi [10] gives various techniques for monitoring tool wear. He also makes a comparative study of the sensors of different techniques and methods in both the principles of direct and indirect measurements of tool wear.

He concludes the optical method which is a direct method to be the best available. But the systems involve laser optics or moving T.V. camera which are expensive.

M. Ikawa, S. Shimada and H. Moorooka [11] have described a photoelectronic displacement sensor consisting of a 50W light source, optical fibre bundles for transmission of the illuminating and reflecting light and photo-diode setup. A high resolution of 0.5 nm and a stability of 1 nm in 20 seconds has been achieved. The frequency has been limited to 1.6 KHz as seen in the graph (Fig. 1.1). The best linearity is when the distance between the fibres and the reflecting surface is

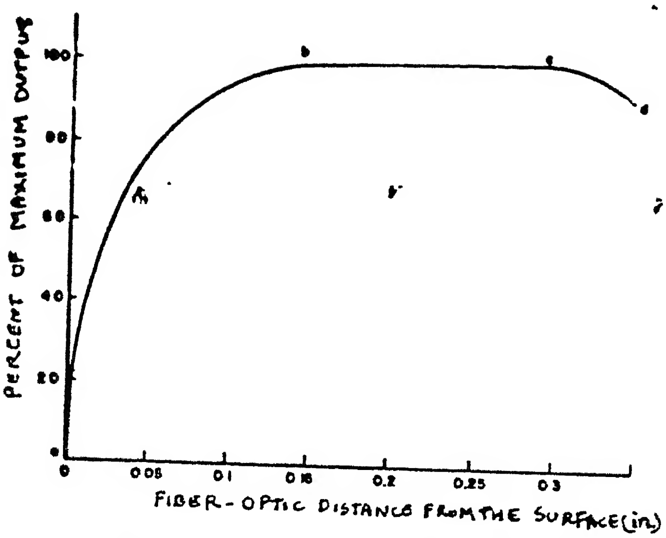


FIG. 1.1 RESPONSE CHARACTERISTIC CURVE.

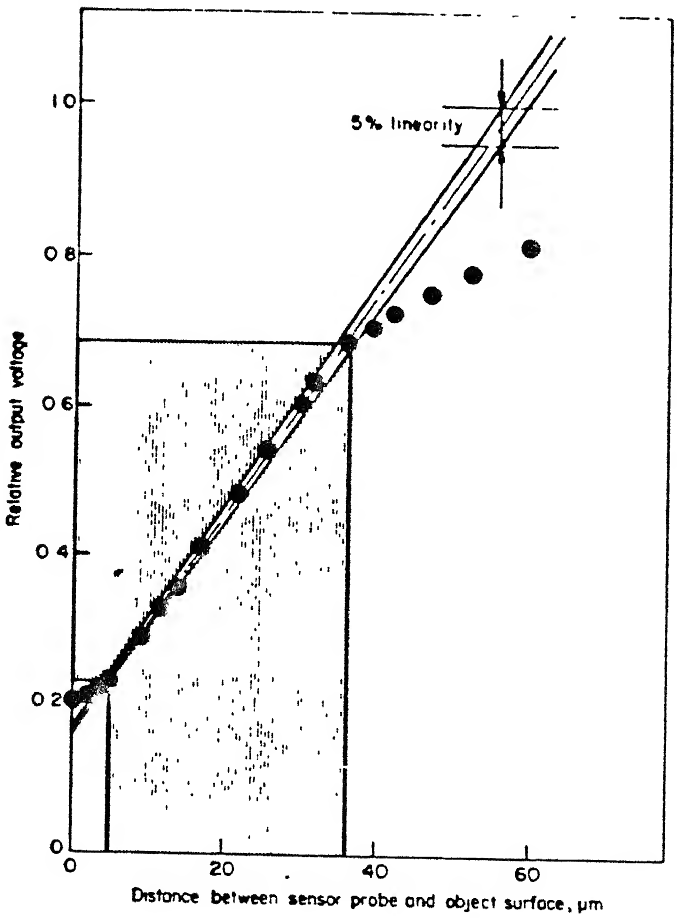


FIG. 1.2 BEST LINEARITY RANGE

between 7 μm and 20 μm (around 5% linearity). Although, it has not been mentioned as to where the photodiode detects maximum intensity of power, The sensor has been calibrated upto a workpiece - probe distance of 60 μm. The nature of the curve beyond 60 μm has not been shown. So close a distance as 30 μm might damage the probe surface,if the workpiece has a poor surface finish. The probe has been calibrated only for flat surfaces. The effect of the probe for measuring cylindrical surfaces has not been discussed. A drift in the sensor has been noted for nominally zero displacement. This is due to the thermal deformation caused by generated heat from the light source. This may be due to the high capacity bulb (50W) used as a light source.

M.S. Sharath [12] (in his M.Tech. thesis work)has carried out experiments on on-line control of machine tool vibrations. For this purpose he modified the displacement sensor developed by Ikawa and others [23] which consists of a light source, a photodetector and a bifurcated bunch of optical fibres as a probe. The high wattage bulb was replaced by a 5 watt bulb as light source to illuminate the workpiece. In order to keep the high intensity constant,a three pin regulator which provides stiff voltage of 12 volts was used. The calibration of this sensor is as shown in Fig. 1.2. The probe gives best linearity when it is at a distance of 2-4 mm from the workpiece.

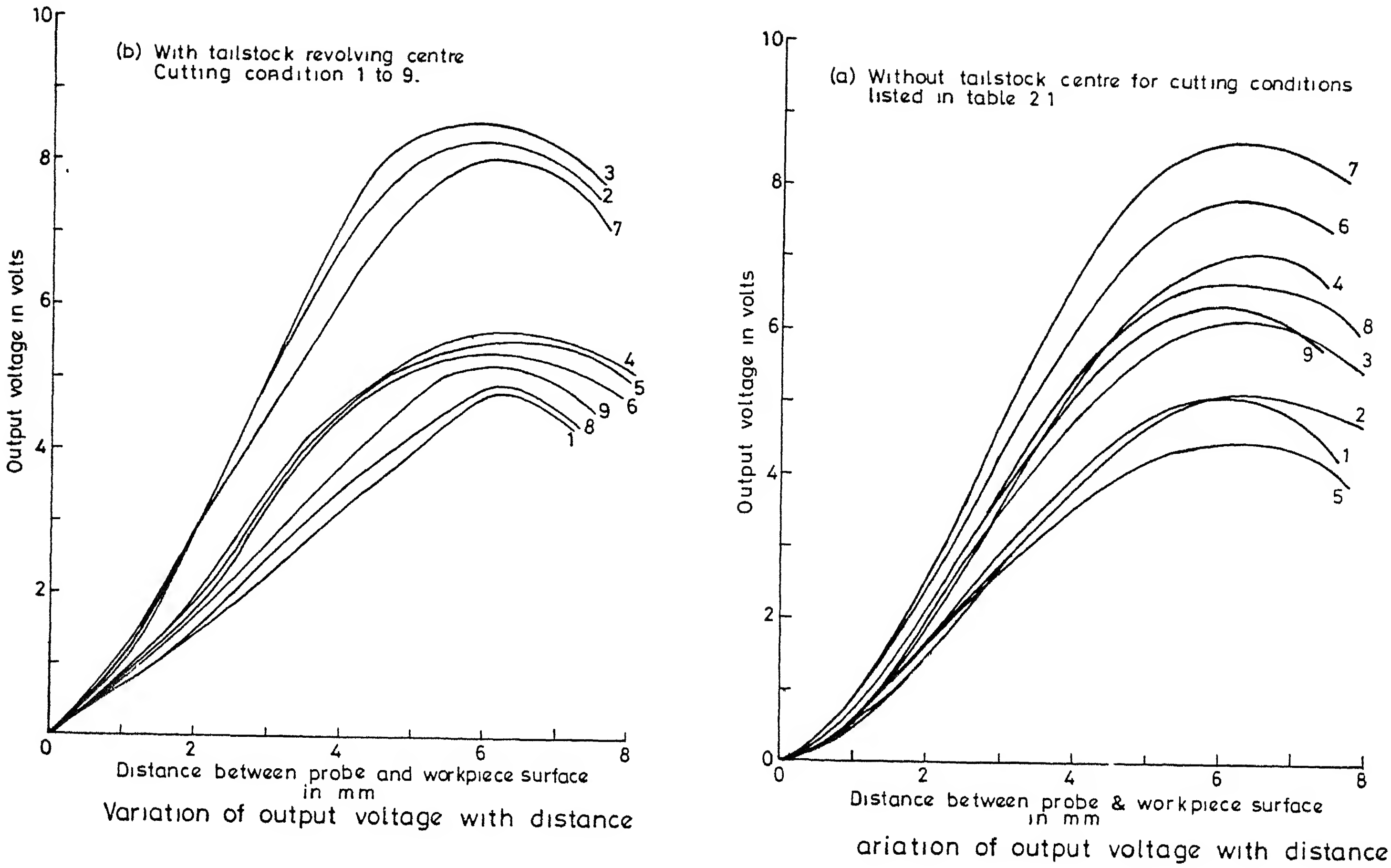


Fig 1.2 Calibration graphs of the optical sensor

Table 2.1 : cutting conditions for static calibration

Cutting Conditions:
Workpiece material: Mild steel
Tool: High speed steel
Workpiece chucked at one end
(a) Without revolving centre
(b) With revolving centre

Sl. No.	Workpiece diameter mm.	Cutting speed m/min	Speed RPM	Feed mm/rev.	Depth of cut mm.	Surface roughness μm (a)	Surface roughness μm (b)
1.	38.52	24.20	200	0.05	0.3	21	20.1
2.	38.52	24.20	200	0.075	0.3	16	12.0
3.	38.52	24.20	200	0.1	0.3	15.5	11.5
4.	38.52	30.25	250	0.05	0.3	13	18.0
5.	38.52	30.25	250	0.075	0.3	20.5	18.5
6.	38.52	30.25	250	0.1	0.3	15	19.0
7.	38.52	38.72	320	0.05	0.3	12	13.0
8.	38.52	38.72	320	0.075	0.3	19	20
9.	38.52	38.72	320	0.1	0.3	17	19.8

1.3 Objectives and Scope of Present Work

Present work is in the field of on-line monitoring of the tool wear for aiding adaptive control. From the past research experiences on sensors it is very much evident that optical measurement gives the best results. Optical methods are used for direct measurement of tool wear. As mentioned by Arsovski and Shirashi [8,10], the optical fibre and photo transistor methods will be helpful only in a discontinuous method of tool wear inspection. The on-line procedure like T.V. camera method is too expensive. But from the research of Ikawa and others [23] the indirect measurement of tool wear is possible by clubbing the idea of optical methods and measurement of workpiece dimension variations. The researchers like Ikawa [23] have not correlated this method for successful monitoring of tool wear.

Present work deals with the on-line monitoring and compensation of tool wear. The objectives of the present work can be briefly mentioned as:

(i) Design of a sensing device to sense the tool wear during machining.

(ii) Design of a tool actuator for constantly positioning the tool in real or discrete time.

(iii) Design of a feed back system to control the variations in the tool wear and workpiece dimensions.

(iv) Study the variations of cutting force due to tool wear during machining with and without feed back.

(v) Experimental investigation of proposed control system on a centre lathe with different cutting conditions.

From the works of M.S. Sharath [12], it is evident that the displacement sensor developed by him gives very good accuracy for flat as well as cylindrical surfaces at various cutting conditions (as seen from the graphs in Fig. 1.2). Also the static and dynamic calibrations of displacement sensor shows very high resolution of 1 μm and the deviation in the linearity was 2.5% within the frequency range of 10 to 500 Hz. Based on the above facts, the same sensor is used on the present work to monitor tool wear.

As tool wears, the distance between the tool tip and the workpiece increases. Hence the workpiece dimension will increase. Therefore the measurement of continuous increase in the workpiece diameter (in the case of turning) would essentially be proportional to the amount of flank wear occurring on the tool.

But the variation in the workpiece diameter may also be due to other reasons namely chatter and ovality. During machining operations as the cutting process proceeds, due to the variation in uncut chip thickness tool chatter will arrive which causes deflection of workpiece. Also the chatter may effect in slight ovality of the work piece. Net effect of all these phenomena will result in varying distance between the workpiece and probe of the sensor.

Since vibration is the to and fro motion of the workpiece from the axis of rotation in the direction of cross-feed, the distance between the probe and the workpiece will vary about a mean point. Hence the output of the probe will also oscillate about a mean point.

Therefore, continuous monitoring of this mean point will be the proportional output of amount of tool wear. The feed back control system should be able to sense the output of the sensor instantaneously (with a minimum lag) at several points and should be able to calculate the mean of these signals.

Next task of the control system is to compare the monitored signal with the reference to produce an error signal and send it to the actuator accordingly.

To achieve this, with the available technology and instrumentation, a microcomputer would have been the best because of the speed at which the microprocessor CPU reads the data, does the airthmetic calculations and makes the decisions. The design of such a control system is also easy because of the well established image of microprocessor based instrumentation and control systems (by both theory and practice).

As discussed earlier because of the flank wear the dimension of the workpiece will increase as the cutting process proceeds. The task of the actuator, therefore, will be to move the tool forward to compensate for the effect caused by tool wear. Effectively the tool holder or actuator should have the following characteristics:

(a) It should be sufficiently rigid not to allow any unnecessary vibrations.

(b) It should be able to move the tool towards the workpiece as compensation during cutting sustaining the resistance from the opposite side.

(c) The sensing device or probe for measuring tool wear has to be held rigidily along with the tool.

(d) It should accommodate the housing of a dynamometer to measure the variation in cutting forces arising due to wear and compensation.

In addition, the tool actuator must be compact.

The exciting force to move the tool may be obtained from mechanical, electrodynamic, electrohydraulic and electromagnetic excitons. In the present work the original tool post is retained as it is and the movements of the tool post is performed by coupling the cross feed shaft with motors so that the whole assembly acts as tool actuator (as in conventional N.C. machines where the tool is positioned by positioning motors).

CHAPTER-2

EXPERIMENTAL SET-UP AND PROCEDURE

On-line control of workpiece dimensions is based on the fact that as tool wears out the distance between the workpiece and the tool top increases. Hence as the machining process progresses, a 'tapering' is noticed along the length of the workpiece. This change in the diameter of the workpiece along its length can be compensated by compensating the tool wear, which can be realized by moving the tool towards the workpiece at a direction perpendicular to the workpiece axis. . A closed-loop feed back circuit is designed to achieve the goal. Feed back circuit includes an optical fibre sensor which produces a signal corresponding to progressive tool wear. This signal after being amplified is passed through the analog to digital convertor and goes to the microprocessor. The microprocessor then, compares this signal with the reference signal and produces an error signal which activates the stepper motor. The stepper motor in its turn rotates the cross feed screw and moves the tool in the direction of cross feed. A schematic diagram of the setup is shown in Fig. 2.6.

2.1 Sensor

As it has been discussed in section 1.3 a photoelectronic displacement sensor has been used in this work for measuring the

tool wear. The sensor is rigidly fixed on the tool holder.

The sensor consists of a light source, a photodetector and a bifurcated bunch of optical fibres on a probe. A 5 watt bulb is used as a light source to illuminate the workpiece surface. A three pin regulator which provides stiff voltage of 12V is used to maintain constant light intensity from the source. The bulb is held rigidly to one of the optical fibre bundles by a collet. Hence, if the light intensity at the receiving fibre varies, it is only due to the variation of the distance between the probe and the workpiece surface. The arrangement of the sensor is shown in Figs. 2.1a and 2.1b.

A photo-transistor is used to detect the variation in the intensity of the light at the receiving fibres. The photo-transistor converts optical signals into electrical signals. The converted electrical signal is further amplified by a high gain operational amplifier. However, it is very difficult to detect the small displacement signals with this system, because the power change in the light transmitted is very small. Therefore, for better and accurate measurement of this weak signal a DC voltage (ref. voltage) of around 4 volts is introduced, with which the actual signal is differentiated. The reference voltage was supplied through a variable multiturn potentiometer. With this set-up the initial voltage level can be set to within ± 1 millivolts. The variation from this level will be proportional to the change in relative displacement

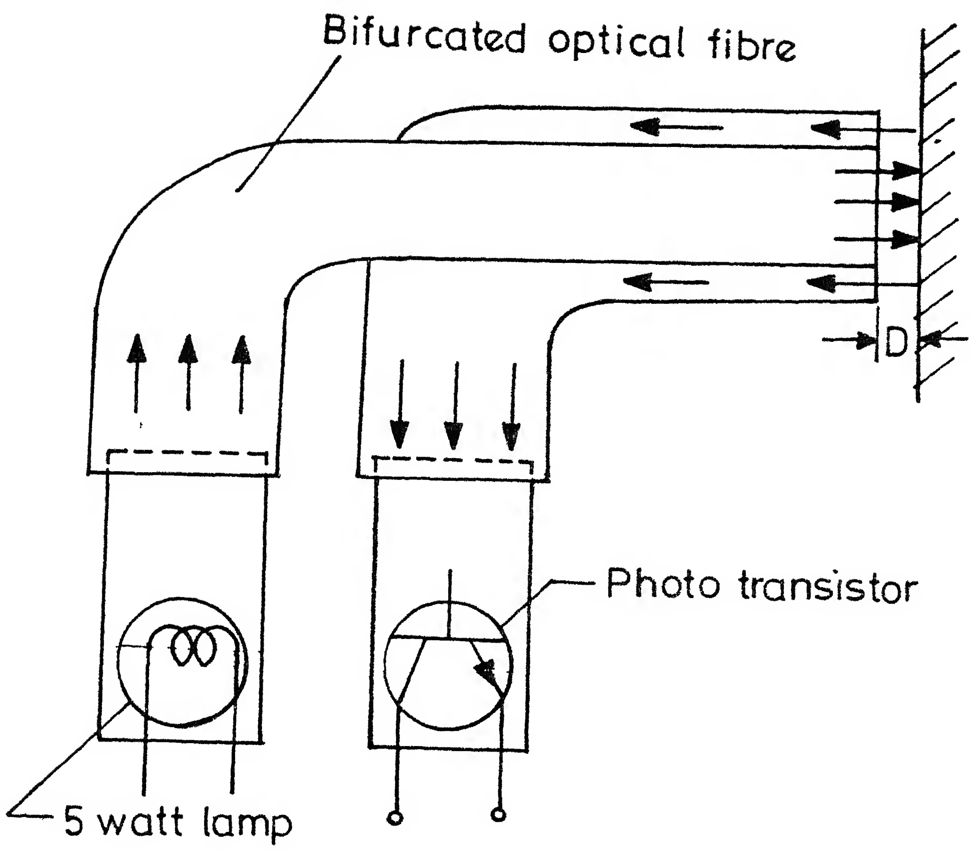


FIG. 2·1a Schematic diagram of a bifurcated optical transducer

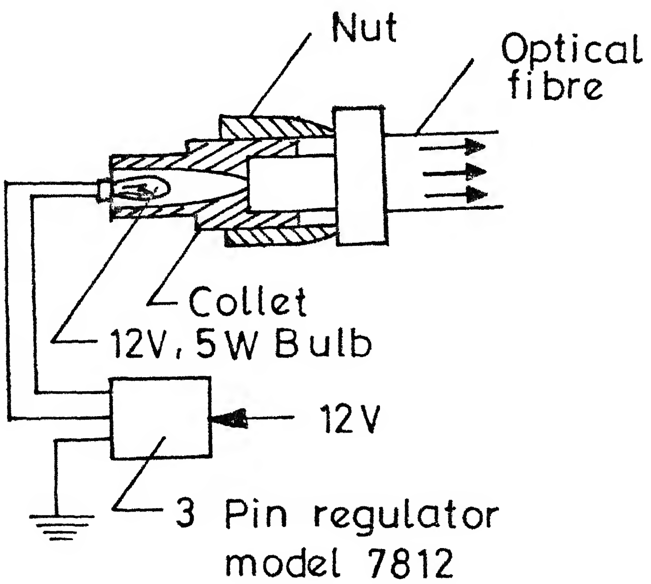


FIG. 2·1b Schematic diagram of the bulb-transducer interface

between the probe and the workpiece surface. The schematic diagram of the sensing circuit is shown in Fig. 2.2.

The phototransistor is to be held rigidly at a constant distance from the probe face so that any detectable change in the output from the sensing circuit can be related to the change in relative displacement only. This is again done by holding the probe with respect to the phototransistor by a collet split nut,which prevents any relative motion between them.

2.2 Design of the Mechanical Parts of the Tool Actuator

It has been stated in section 1.3 that the tool actuator includes sensor, dynamometer, tool post, coupling for the cross feed screw and positioning motor and the fixture to hold and carry motor along with carriage.

Since tool is fixed rigidly to the dynamometer, the dynamometer positioned in the place of normal tool post on the compound rest will serve the purpose.

The position of the optical probe should be such that

(i) It is rigidly fixed to the carriage and completely isolated from the machine tool vibrations so that absolute change in the relative distance between probe and workpiece can be measured.

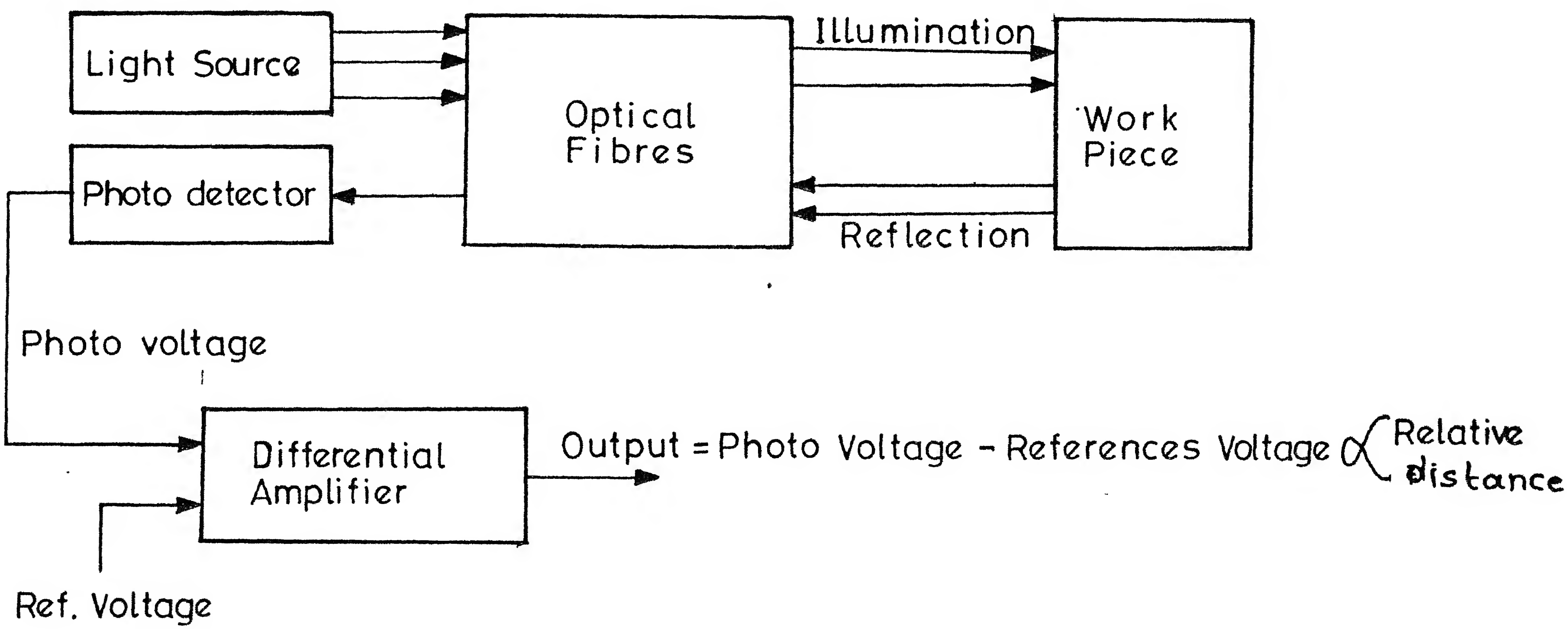


FIG. 2.2 Block diagram of the sensing circuit

(ii) The height of the probe position must coincide with the axis of the workpiece.

(iii) Probe face should be located at a distance of 2mm from the workpiece because, from the calibration graphs shown in Fig. 1.2 it is seen that the best linearity and sensitivity are obtained when the distance between the probe and the workpiece surface is from 2 mm to 4 mm.

(iv) Main purpose of the probe is to monitor the tool wear. Hence the tool and the probe should be in the same axis so that the changes in workpiece dimension with respect to tool wear are monitored instantaneously.

Considering all the above mentioned points, it is decided to place the probe in-line with the tool and exactly opposite to tool on the other side of the workpiece. A fixture as shown in Fig. 2.3 is made and the base of the fixture is attached to the compound rest. This makes it possible for both the tool and probe move equally and simultaneously. The fixture is made of perspect material and it is mounted on the base plate. Rubber sheets are placed wherever there exists a joint so as to damp the vibrations occurring from the base due to machine tool-workpiece interaction. The optical probe is placed in the circular spacing of the fixture between two blocks and held rigidly by tightening the screws. Therefore, the tool and the probe

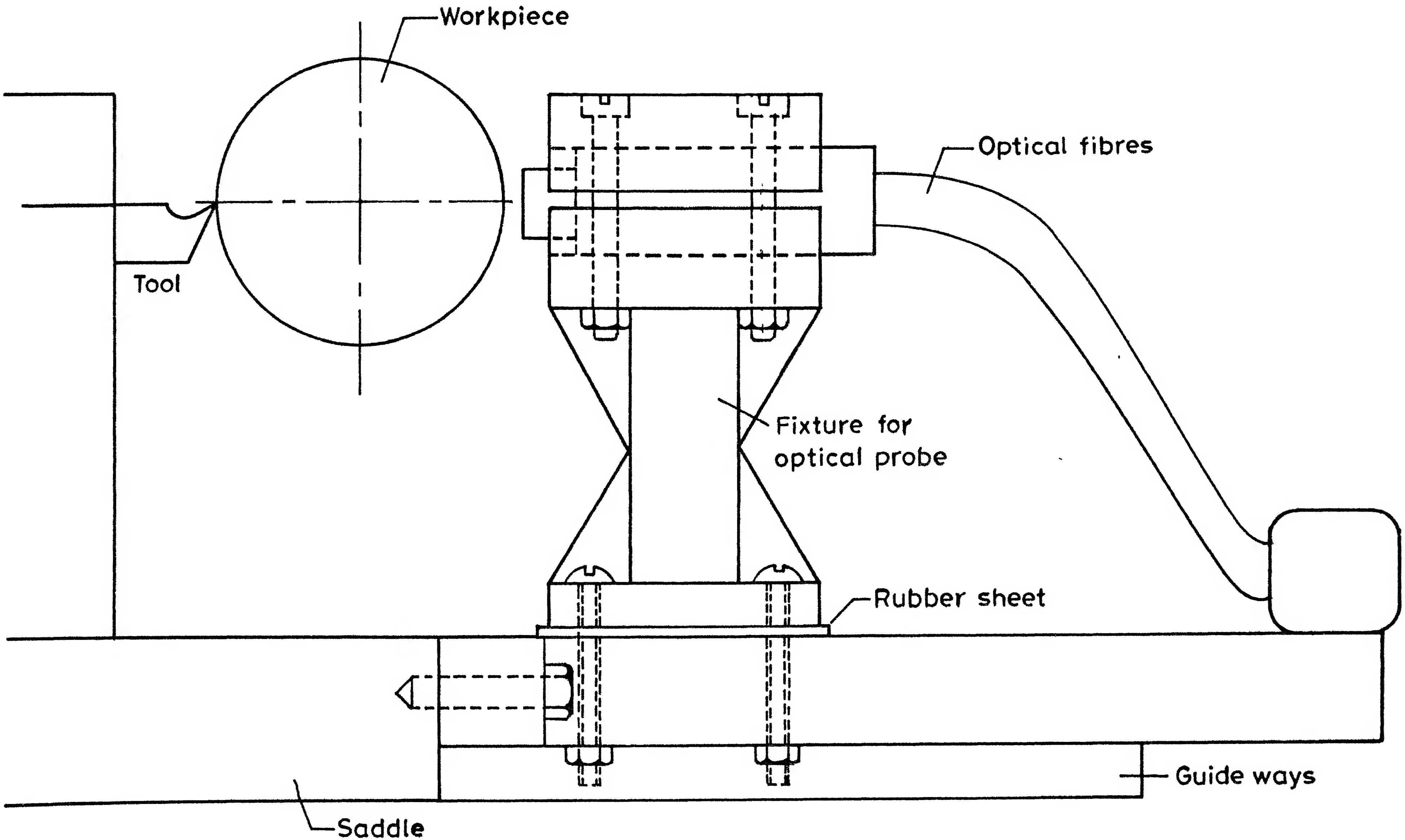


Fig. 2.3 Figure showing the optical probe mountings on the lathe.

along with the fixture and the tool holder constitute a rigid body. By this arrangement the probe can be placed at any desirable distance from the workpiece. Once the distance is set, the screws are tightened so that the probe in fixed permanently.

Since the motion of tool as compensation will be very small (in μm) the amount of rotational input given to the crossfeed screw should also be very small and accurate. For this purpose a stepper motor is used. Stepper motor has very high accuracy of rotation with the least count of single step equal to 1.8^{o}. The second advantage of stepper motors over D.C. servomotors is that they do not require any further monitoring of their positioning with a feed back.

Next task is to fix the stepper motor rigidly to the crossfeed shaft. For this purposes a fixture as shown in Fig. 2.4, is designed and fabricated. The fixture is cast and then machined for the required dimensions. It is mounted on the carriage with the help of fastening bolts. The stepper motor is attached to the fixture by means of screws. Original fly wheel of the cross feed shaft is removed and the shaft of stepper motor is coupled to the cross feed shaft by the coupling shown in the Fig. 2.4. The coupling is made of brass.

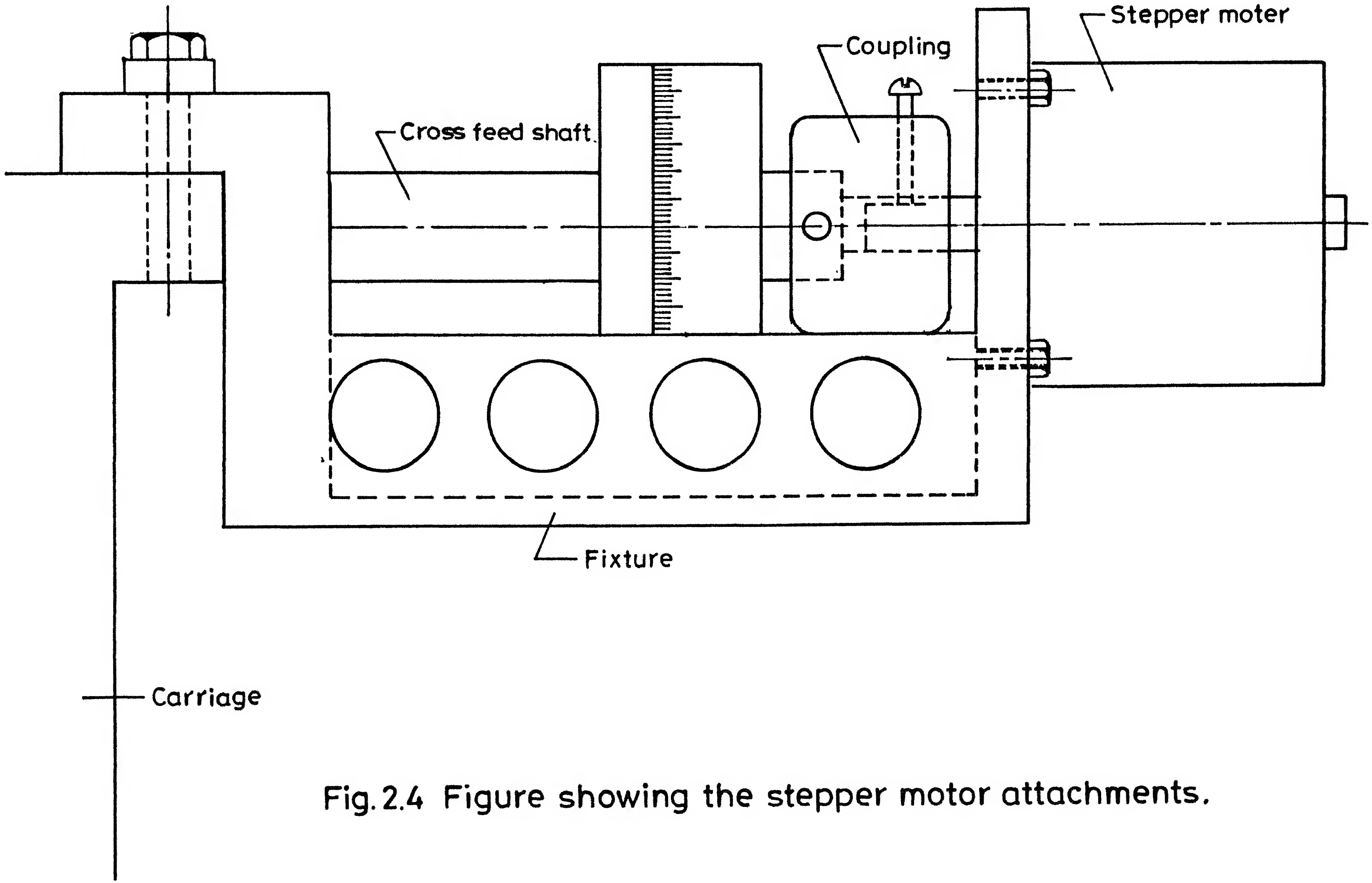


Fig. 2.4 Figure showing the stepper motor attachments.

2.3 Feedback Circuitry and Instrumentation

2.3.1 Feedback Elements

As stated in Section 1.3, the output of the photo-transistor is small and it needs to be amplified to a suitable gain.

Figure 2.5 shows the circuit for the amplification of the optical sensor output signal. For the purpose of sensing and recording the wear magnitude a high impedance recorder is used. The output of the amplifier is bifurcated in two channels. One channel is fed to the recorder to continuously record the output of the sensor. Other channel is fed to the analog to digital convertor of the microprocessor kit. Anagolog to digital convertor converts the analog input to their digital equivalent.

2.3.2 Controller

The digital signals from ADC are supplied to the microprocessor for comparison with the set reference. After the calculation of error, a proportionate signal for compensation is to be generated by the microprocessor. Considering the difficulty involved in the hardware, a microprocessor kit which contains all the essential peripherals for the control application like serial and parallel I/O channels, analog to digital and digital to analog convertors, RAM, ROM and EPROM facility for storing

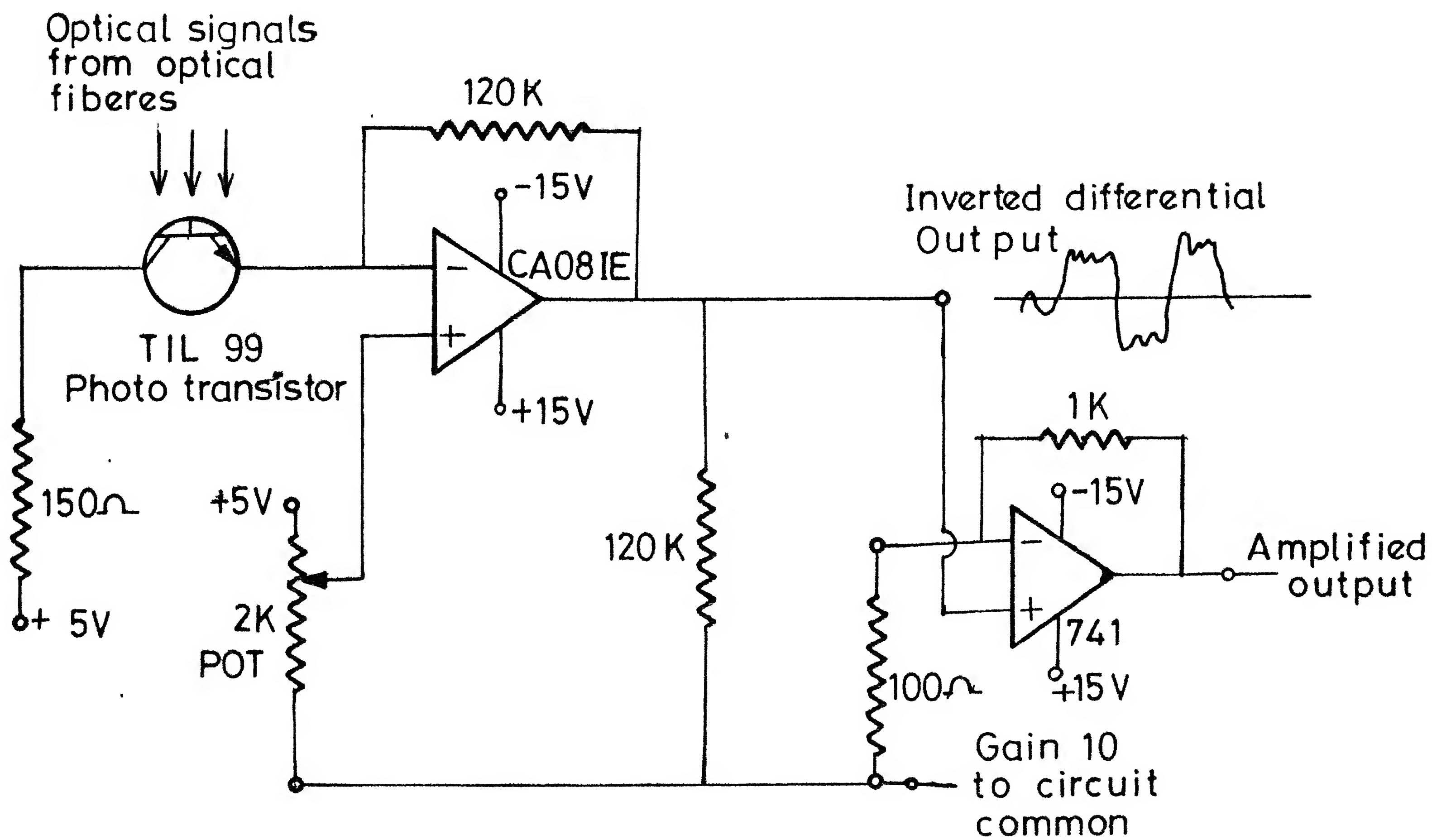


FIG. 2.5 SENSING CIRCUIT

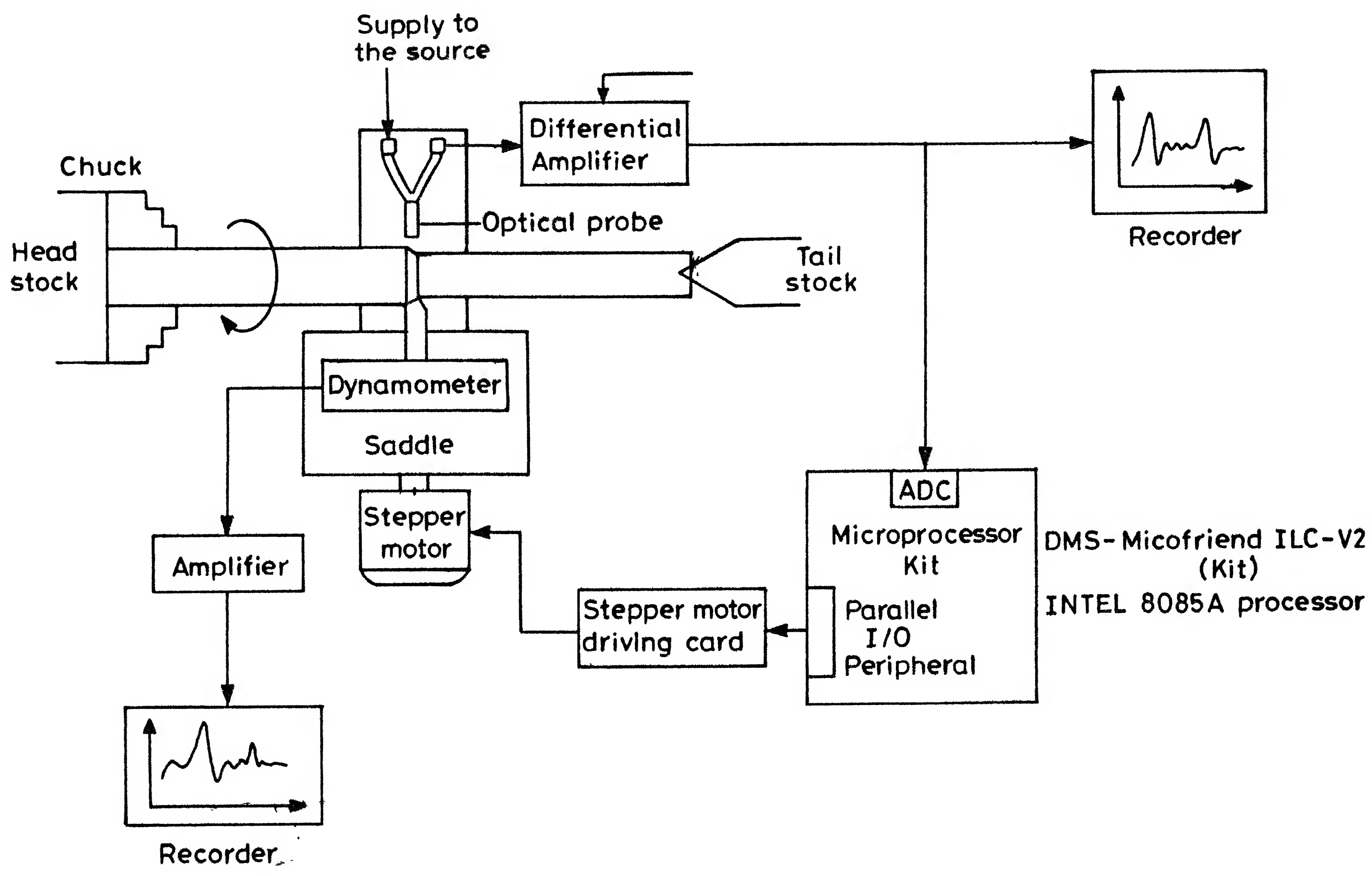


Fig. 2.6 Schematic diagram of the control system.

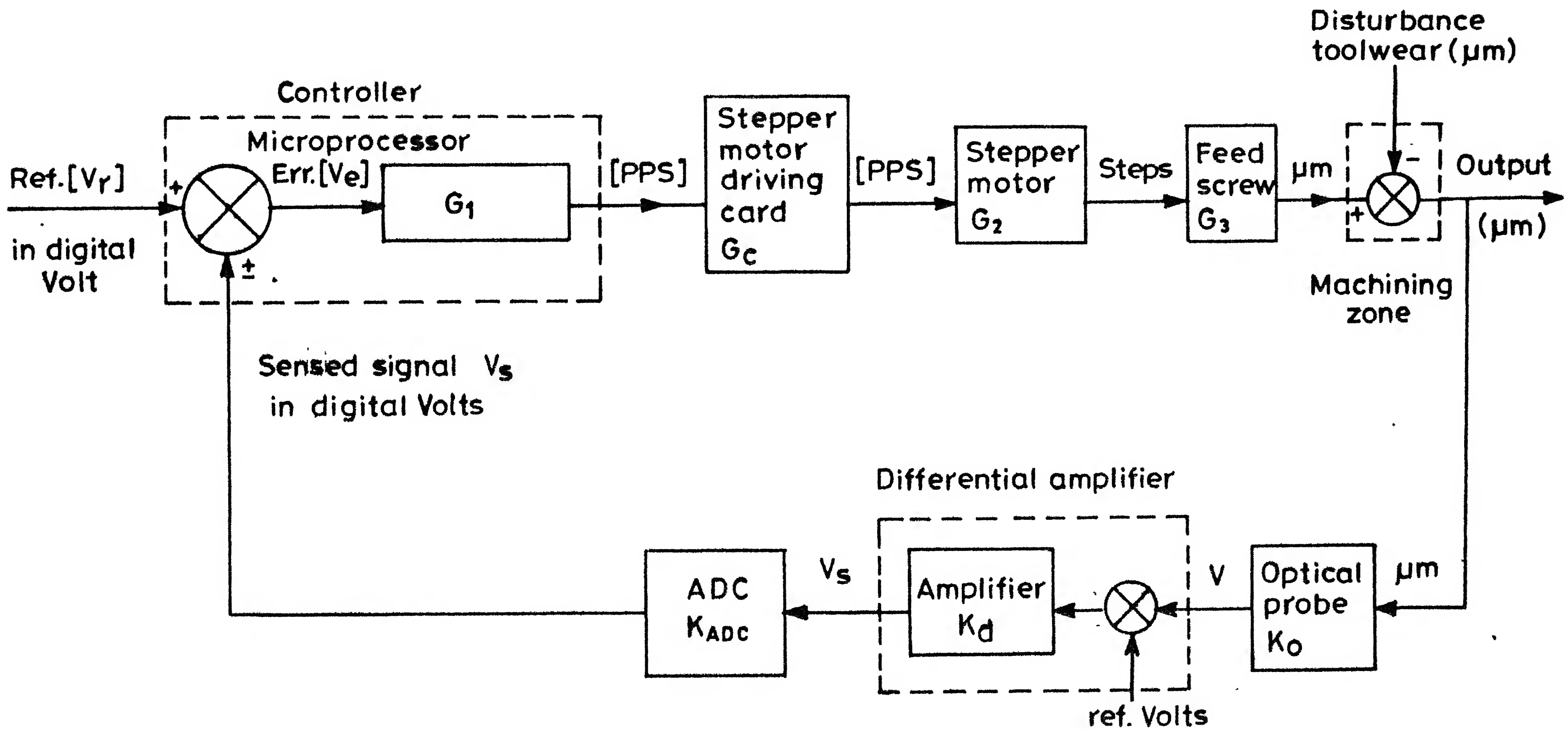


Fig. 2.7 Block diagram of the control system.

Step	Ph1		Ph2		Hex Data
	A1	B1	A2	B2	
1	0	1	0	1	5
2	0	1	1	0	6
3	1	0	1	0	9
4	1	0	0	1	A
5	0	1	0	1	5

Table 1. string of data for driving the motor.

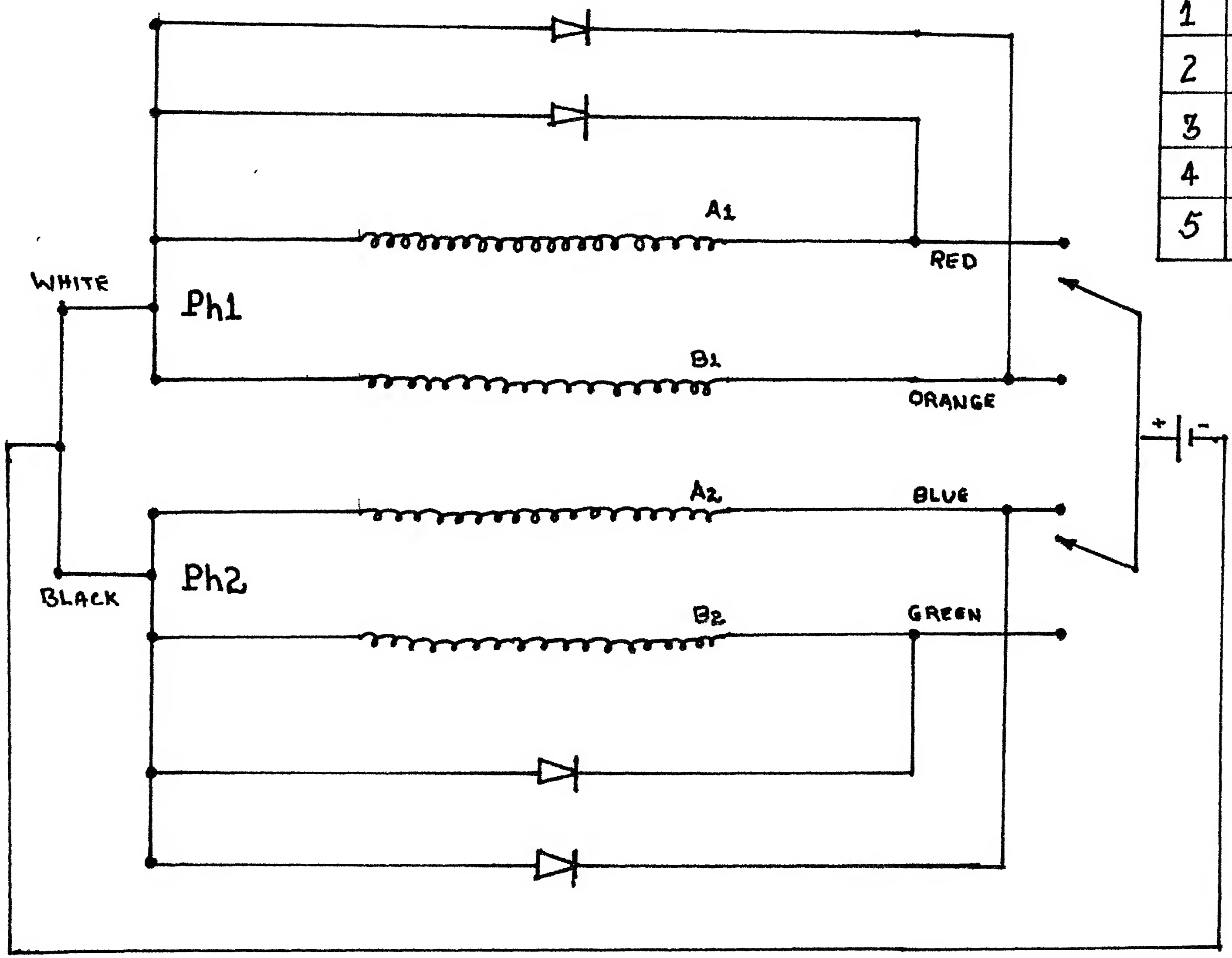


FIG.2.8 Schematic diagram of Stepper motor layout.

is selected as a controller. The complete information about the microprocessor kit used for the above purpose is given in Appendix-III. Figure 2.6 shows the schematic diagram of the control system and Fig. 2.7 shows the block diagram of the control system.

2.3.3 Actuator

As described in Section 2.2, the stepper motor coupled with cross feed shaft forms the actuator. Fig. 2.8 explains the layout of the stepper motor. There are two coils Ph1 and Ph2 with center tappings, which divides the coils in to A1, B1 and A2, B2 respectively.

To energise the coil, if 'A' end of the coil is made 'high' then 'B' end has to sink the current through the coil. Therefore, the coil drivers have to be both, the 'sourcing' and the 'sinking' type.

There is a string of data that is to be supplied to the coils which is shown in Table 1. Each of this string when send out in the sequence shown would result in a 'step' rotation in a certain direction. From the series of data it is noted that at a time only the polarity of a single coil is reversed. If the order of the data sequence is reversed, the direction of rotation of the motor also gets reversed.

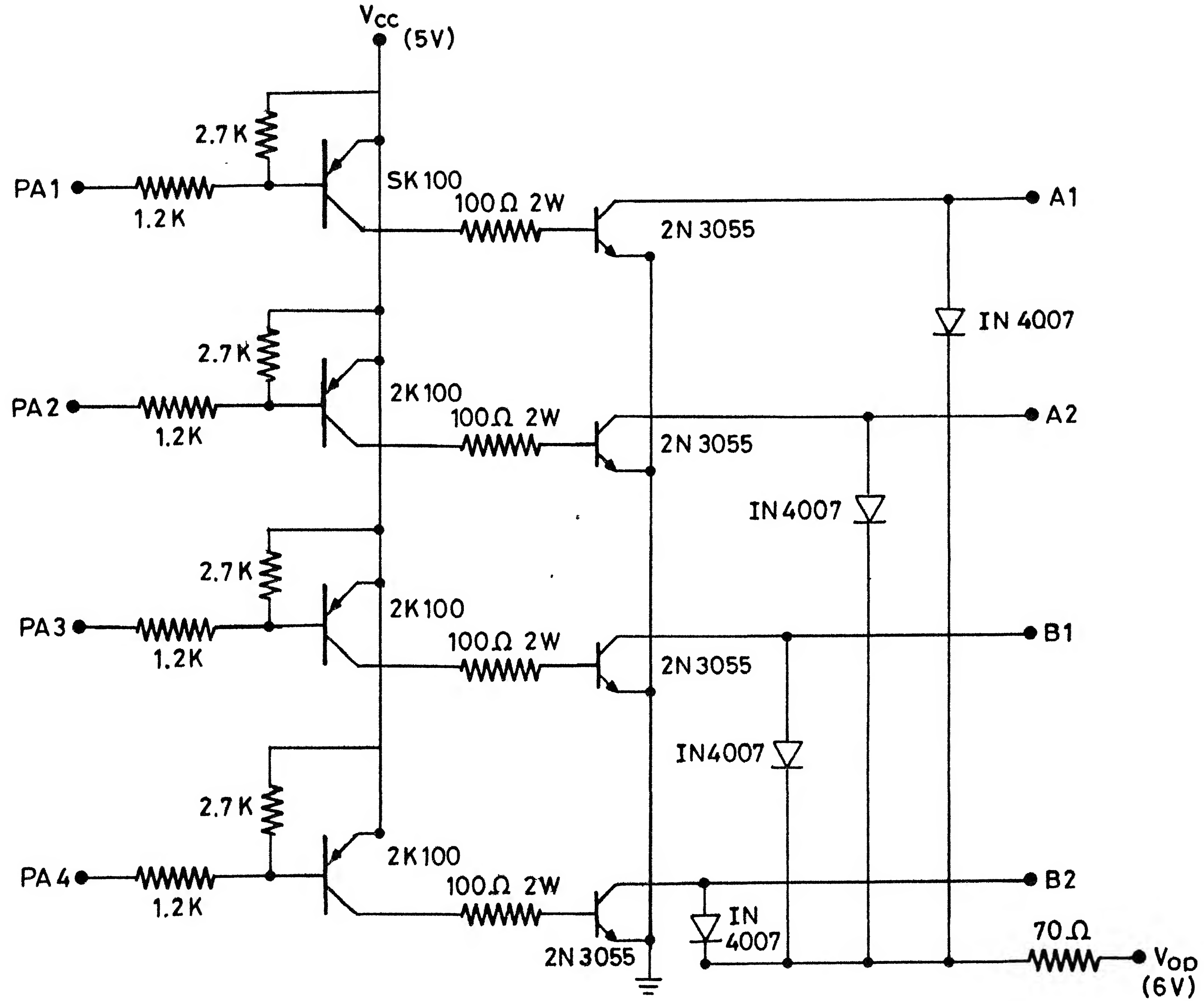


Fig. 2.9 Diagram for the stepper motor driving circuit.

The '1' in the table indicates current flow through the coil while a 'o' indicates no current flow.

This sequential string of data is generated in the Intel 8085A microprocessor to directly output the sequence to the parallel output port lines of the INTEL 8255 programmable peripheral interface.

Thus generated output provides very less current. A driving circuit (using 'Transistor switches') is employed to boost the current handling capacity of the output signals to drive the motor windings. Fig. 2.9 shows the diagram for stepper motor driving circuit.

2.3.4 Decision Making

The use of a microprocessor kit makes it easy for decision making since the microprocessor can be programmed using "Assembly" language. Decision making through software is easy because of the simplicity involved and also it can be altered very easily for the necessary changes in the control environment.

As stated earlier, the first step involves calculation of the mean value about which the output of the sensor oscillates (due to vibration and other effects). This involves reading the data in a time specified by the period of oscillations, summing up all these data and dividing the sum by total number of readings. This mean value which gives

the monitored or sensed signal is compared with the reference value to determine the error. This error denotes effectively the change in distance between probe and workpiece.

To make the programme easy, the division process in the calculation of mean value is eliminated. To compensate for this the actual value of reference is multiplied by the total number of data read and this product is set as the reference value. The corresponding error will also be the multiple of total number of data read.

Depending upon the error which is positive or negative and calibration curve of the sensor, we can determine whether the distance between the probe and workpiece has decreased or increased. By the concept of flank wear, the effect of wear will always result in increasing the dimensions of the workpiece. This always results in positive type of error which goes on increasing with machining. If the amplitudes of vibration of the workpiece are very high, which may happen due to cutting conditions and clamping conditions, there are chances of reduction in the magnitude of error.

Now, depending upon the magnitude of error, stepper motor rotates in clockwise direction (which makes the tool move forward) by proportional number of steps. For these many number of steps the string of data given in Table 1. is produced by the microprocessor through the parallel I/O lines. This gives the compensation for the measured tool wear.

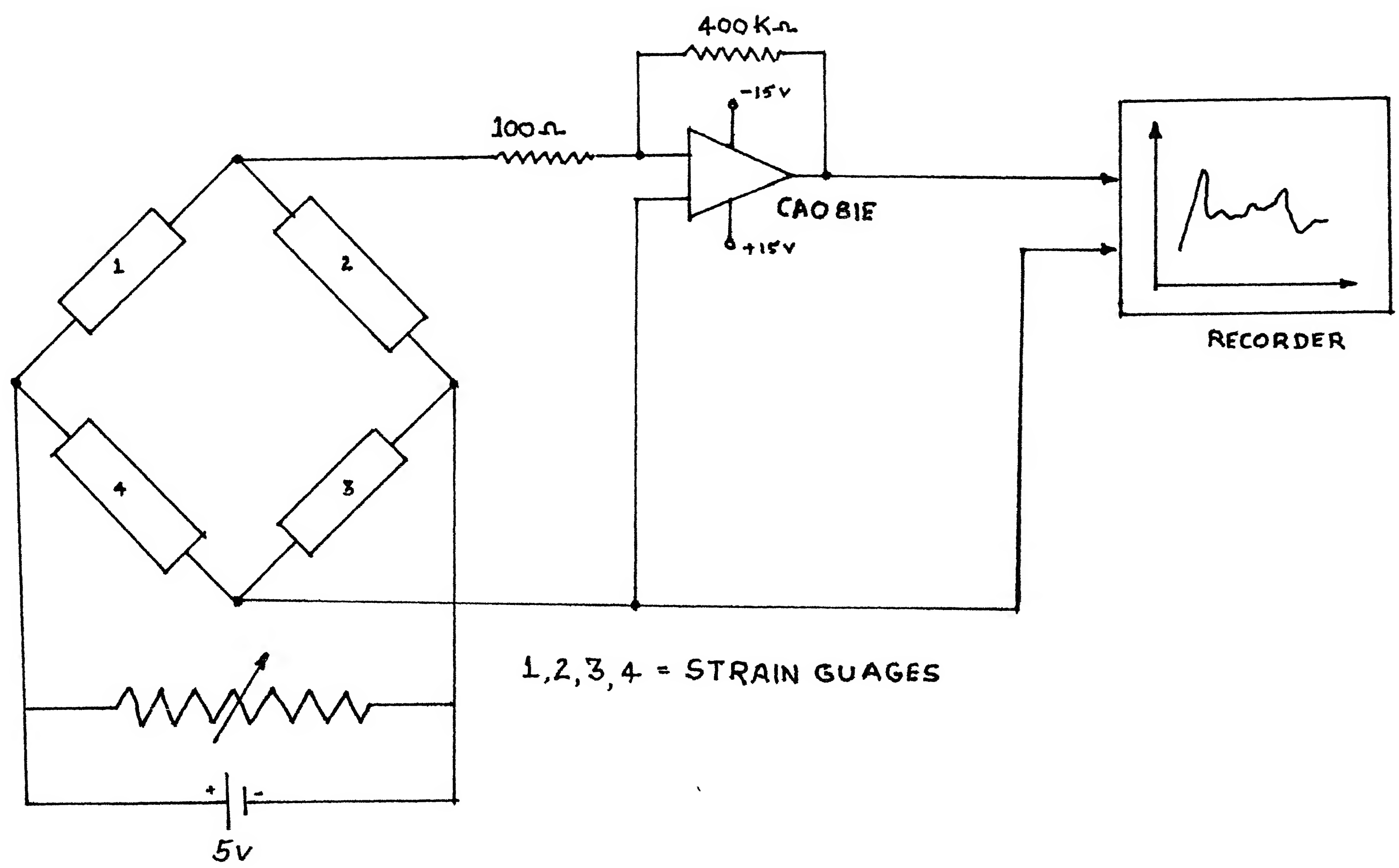


Fig. 2.10 Diagram of the Dynamometer bridge and Amplifier.

2.4 Dynamometer

To study the effect of tool wear and compensation a dynamometer is used to measure the feed force coming on the tool while machining. Since the output of the dynamometer will also be very small, the signals are amplified and then recorded in a recorder. Fig. 2.10 shows the circuit diagram of the dynamometer bridge (wheat stone's bridge) and amplifier. This is used to monitor the effect of wear and compensation on the machining processes and tool life.

2.5 Experimental Procedure

A series of experiments was conducted to determine the performance of the control system. Experiments were conducted on two different materials namely mildsteel (hardness HRC=9) and EN8-steel (hardness HRC=16) for different machining conditions.

2.5.1 Procedure

The workpiece was clamped in a four jaw chuck and supported at the tailstock by a revolving centre. The workpiece was first rough turned. This operation was necessary to remove the ovality and eccentricity of the workpiece. Keeping in view thefinishing operations, small values of depth of cut were choosen for experiments.

As the tip of the probe is of circular shape, the tool position in the longitudinal direction was adjusted by the compound rest so that the tip of the tool and the edge of the probe lie in the same line opposite to each other. This makes the probe axis lag the tool by a certain distance.

To set the initial voltage level of the transducer (reference point), the workpiece was turned to a certain length. Then the tool from the toolpost was removed and ground to set angles using tool and cutter grinder so that the tool has a minimum nose radius (pointed tip). This tool was placed in its position. Afterwards the probe was mounted on the fixture and the distance between the probe and workpiece was adjusted to 2 mm. Then the probe was clamped firmly.

The ADC used has a restriction on the analog voltage input (0 to + 5V) for digital conversion. For safe operation within the specified range, the output of the sensing circuit was set to +1.5V by the potentiometer and given to feed back circuit. Therefore, even with no sensing signal we get an output of +1.5V from the feed back circuit. The signal from the sensing circuit was also recorded in an Omni Scribe recorder.

In the control system, the key board of the micro-processor was used as a switch. Closing of the feedback circuit was done by executing the programme in the memory by pressing

the 'RUN' command key on the board. Opening of the feed back was done by pressing the 'RESET' key which brakes the execution of the programme.

Experiments were carried out for various feeds and depths of cut and for two spindle speeds of 270 rpm and 420 rpm. For each experiment, a newly ground tool was used. After positioning the newly ground tool and probe and setting the initial voltage level of sensing circuit, the feed was adjusted in the feed gear box. Then the machine was switched on and cutting was carried out for a certain distance without the feedback circuit. As the machining process starts, the tool wear also begins and signal of the tool wear was recorded by the recorder. After certain time, the feedback is given by pressing the key on the key board. The response of the sensor with feedback was recorded.

Later, feedback circuit was closed once the machine was switched on and the response of the sensing circuit was also recorded. Like this some more experiments with continuous feedback were carried out.

To verify the monitored results of the tool wear as well as its compensation, after the experiment the tool profile contour was recorded using the shadowgraph. The amount of tool wear from the shadowgraph record and the monitored signal in the Omni Scribe recorder were compared.

To investigate the effect of tool wear and compensation on the tool, a dynamometer was mounted on the compound

rest and experiments with continuous feedback were carried out. In these experiments, in addition to the signals from the sensing circuit, the signal corresponding to feed force was also recorded.

2.5.2 Description of the Programme

The programme was written in such a way that the microprocessor sets a constant reference signal and produces an error or control signal by comparing it with the sensed signal.

Since the initial distance between the probe and the workpiece incorporating the beginning of linearity range (see Fig. 1.2) cannot be set accurately, the first reading of the sensed signal was considered to be the reference value. This constitutes the first stage of the programme. The Fig. 2.11 shows the flow chart for setting the reference value.

To move the stepper motor for compensation the string of data which are in a cyclic order had to be generated by the microprocessor. These strings were generated proportional to the error signal. The second stage of the programme consists of a continuous loop to run the stepper motor. This loop consists of four parts. Each part consists of data generation for one step and a subroutine. This subroutine is common for all parts. The error signals were produced in the subroutine. The flow chart for the second stage is as shown in Fig. 2.12.

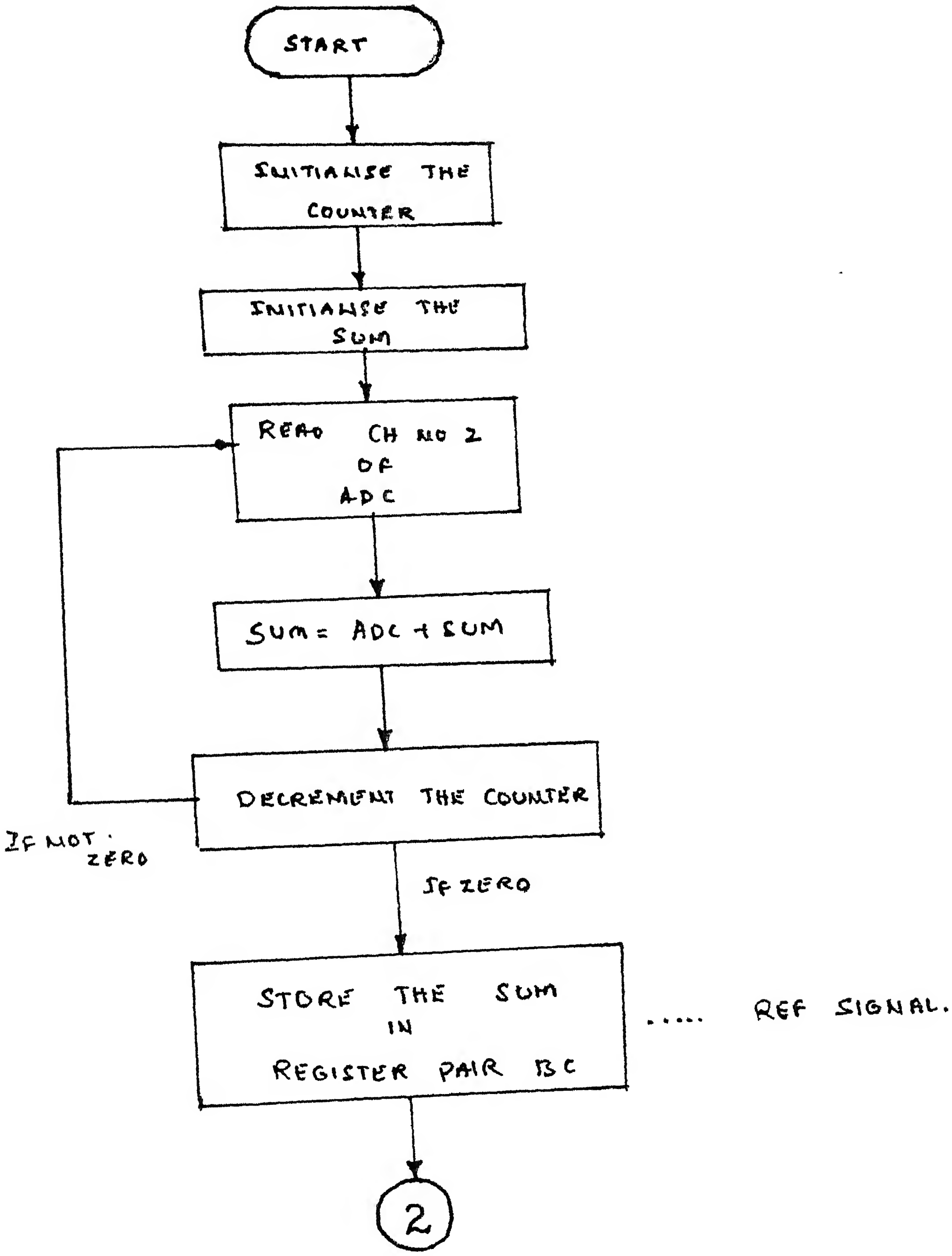


Fig 2.11 Flow chart for setting the reference value

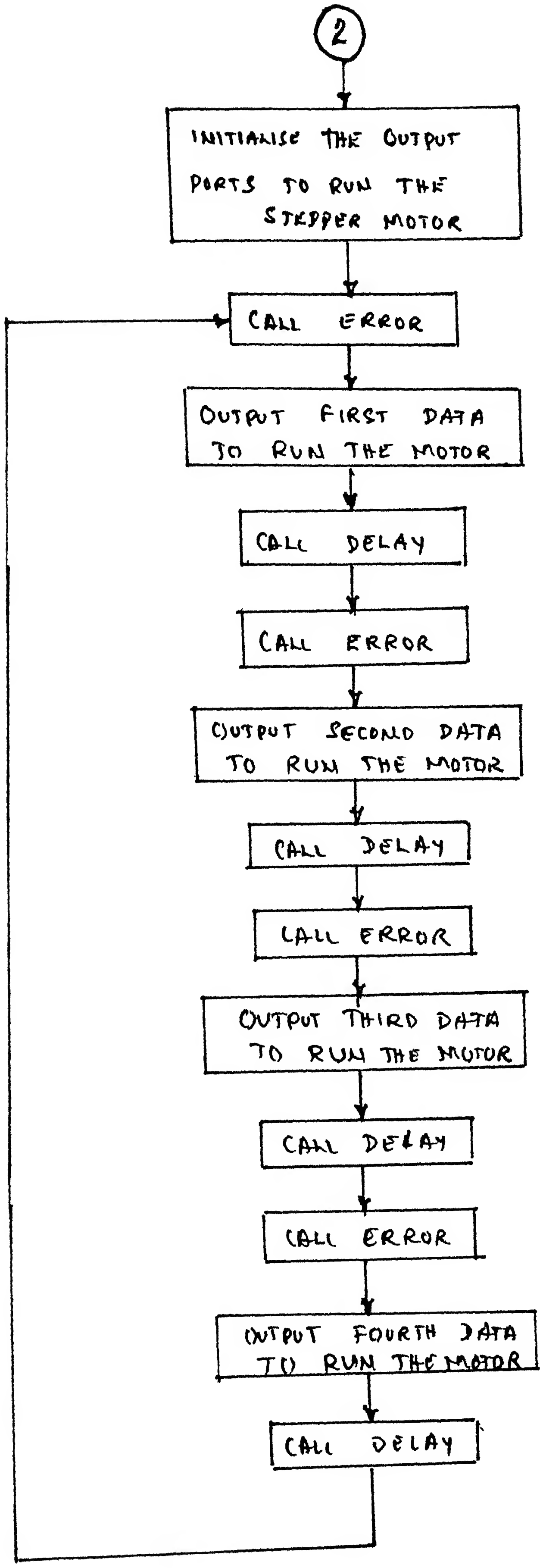


Fig 2.12 Flow chart for driving the stepper motor.

The subroutine consists of a programme to measure the sensed signal, compare it with the reference signal and calculate the error. If the error is positive (which measures the amount of tool wear) then proportionate number of steps is calculated and the subroutine returns to the main programme. The number of steps was calculated by setting the value of error for one step. If the error is negative the control goes back for measuring the sensed signal and the loop continues till it arrives at a number for rotation of stepper motor. The Fig. 2.13 shows the flow chart for the error subroutine.

In addition to the error subroutine many other routines for reading the ADC and time delay were used at several stages of the programme. The complete programme is listed in Appendix-IIIC.

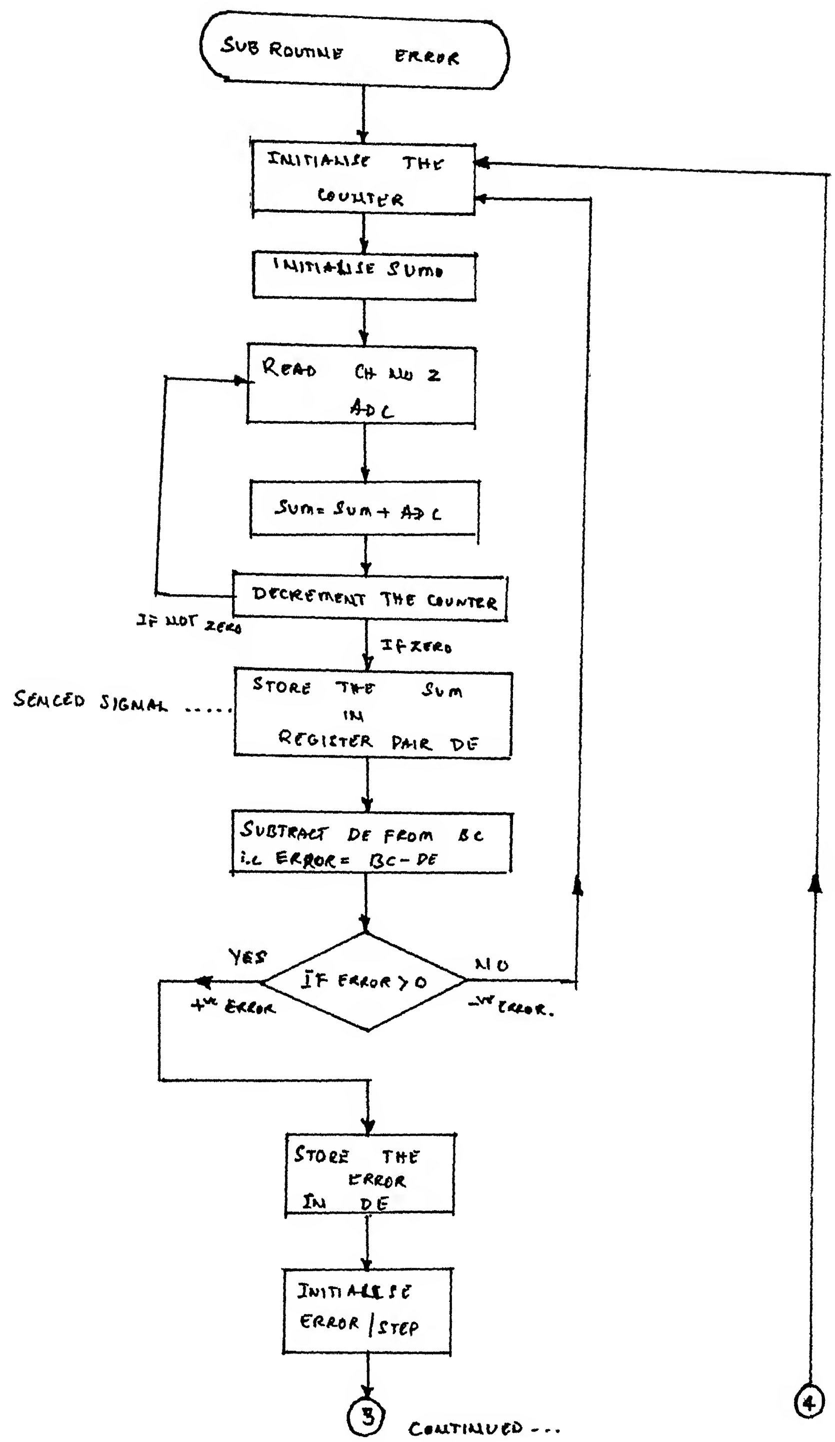
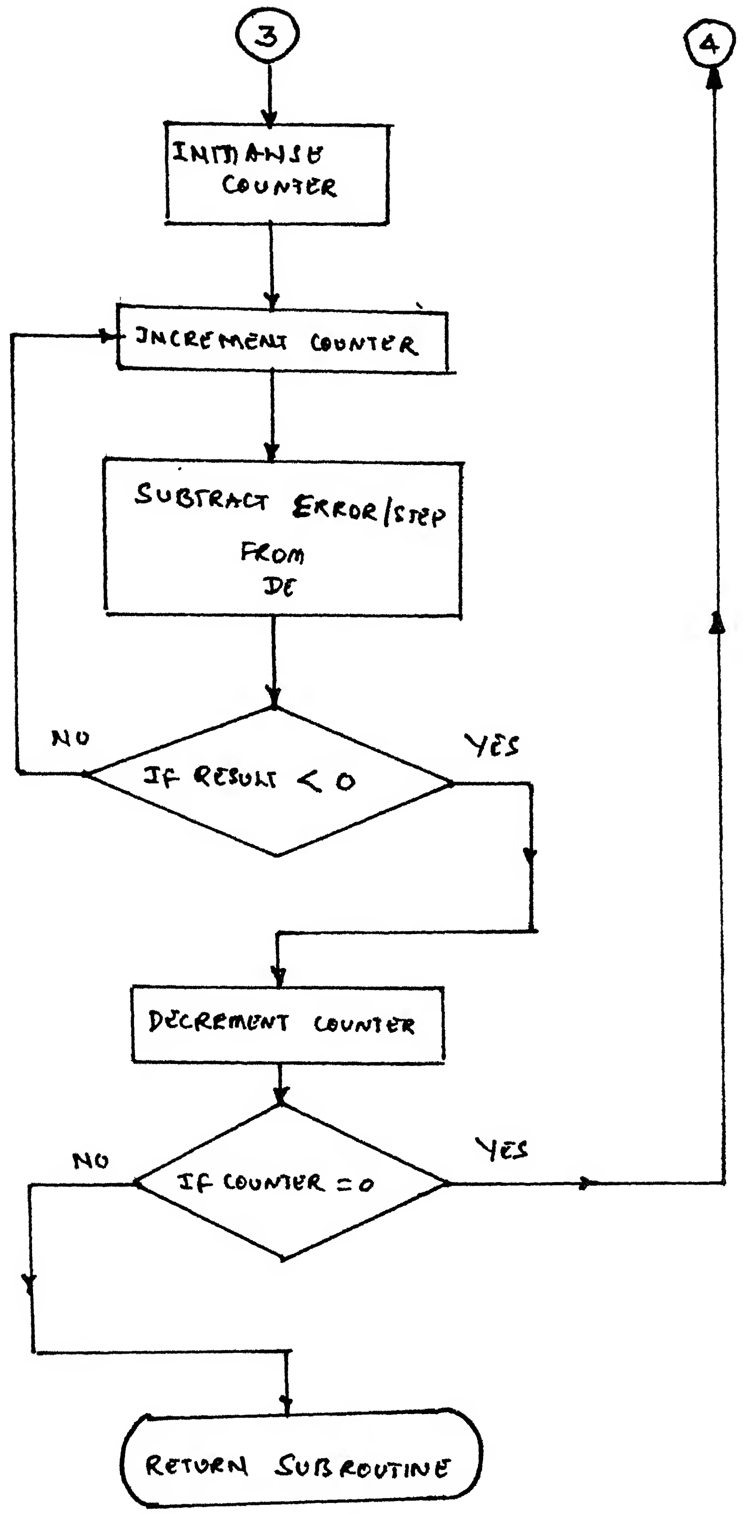


Fig 2.13 Flow chart for error subroutine



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CHAPTER-3

RESULTS AND DISCUSSIONS

3.1 Results

Several experiments were carried out to investigate the performance of the control system. The various conditions under which experiments were carried out are listed in Table 2. The different results obtained by experiments are as shown in the Figs. 3.1 to 3.11.

3.2 Discussions

Fig. 3.1 and Fig. 3.2 show the output of the optical sensor, for both with and without feedback during the machining of mild steel. The graph from A to B shows the steady increase of dimension due to tool wear and the region B to C denotes the compensation given for tool wear.

Figs. 3.3 to 3.8 show the output of the optical sensor in the case of machining EN8-steel. In these graphs, the regions AB, CD, EF indicate the tool wear and regions BC, DE etc. indicate compensation given for tool wear.

From all these graphs it is evident that the raising portion from the initial point indicates the tool wear and the falling portion indicates the compensation. Since the

x-axis for all the graphs is time, it can be clearly seen that the system response in sensing and compensating is very fast (as desired). But in Fig. 3.7 and Fig. 3.8 the output signals from the sensors seem to vary very much. The reason for this is the domination of chatter vibration over tool wear.

Figs. 3.9a and 3.10a show the output of optical sensor and Figs. 3.9b and 3.10b show the corresponding feed force variations for a continuous feedback case. From these graphs it is confirmed that the forces acting on the tool will gradually increase due to tool wear and a sudden increase in the force is also observed at the time of wear compensation. The reason for this is that as the tool wears, the contact area with the workpiece will be more,hence the gradual increase in force on the tool. When the compensation is provided, the tool is moved forward which results in more area of contact resulting a sudden increase in the force acting on the tool.

The amount of tool wear is measured from the graphs. These values are compared with the shadow-graph results. The compared results are given in Table 3. From this comparison, it is observed that the response of the system is accurate.

Table 2 : Machining Conditions for the Experiments

Sl.No.	Material	Spindle speed N rpm	Cutting speed m/min	Feed mm/rev	Depth of cut mm	Material Hardness R_c
1	Mild steel	180	33.9	0.09	1	9
2	Mild steel	270	46.65	0.05	1	9
3	EN8-steel	270	42.4	0.1	1	16
4	EN8-steel	270	33.9	0.07	0.75	16
5	EN8-steel	420	46.1	0.05	0.5	16
6	EN8-steel	420	43.5	0.1	0.5	16
7	EN8-steel	420	42.22	0.13	1	16
8	EN8-steel	420	40.9	0.15	1	16
9	EN8-steel	420	38.26	0.04	0.5	16
10	EN8-steel	420	36.9	0.07	0.6	16

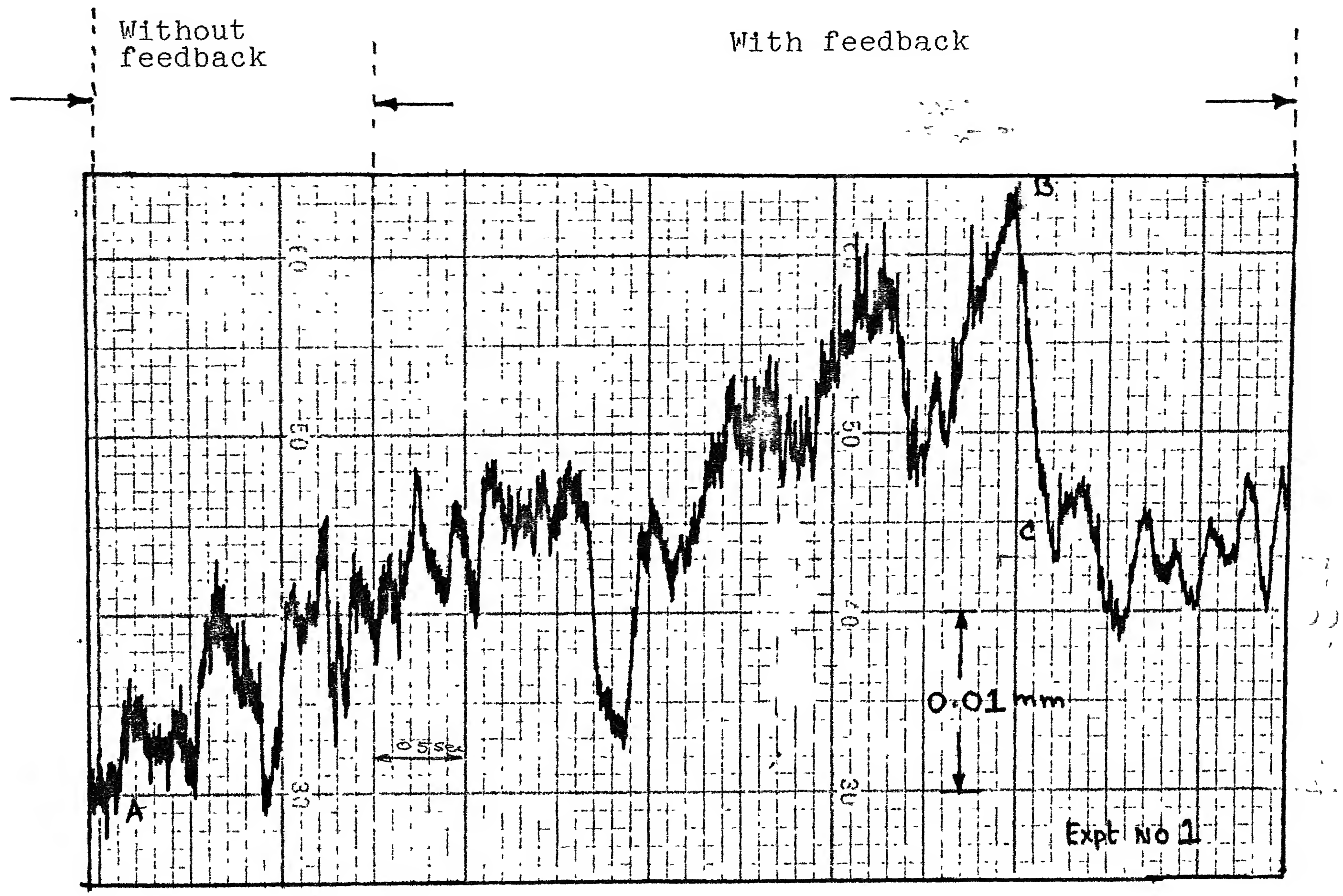

Fig. 3.1 : Optical Sensor Signal Pattern

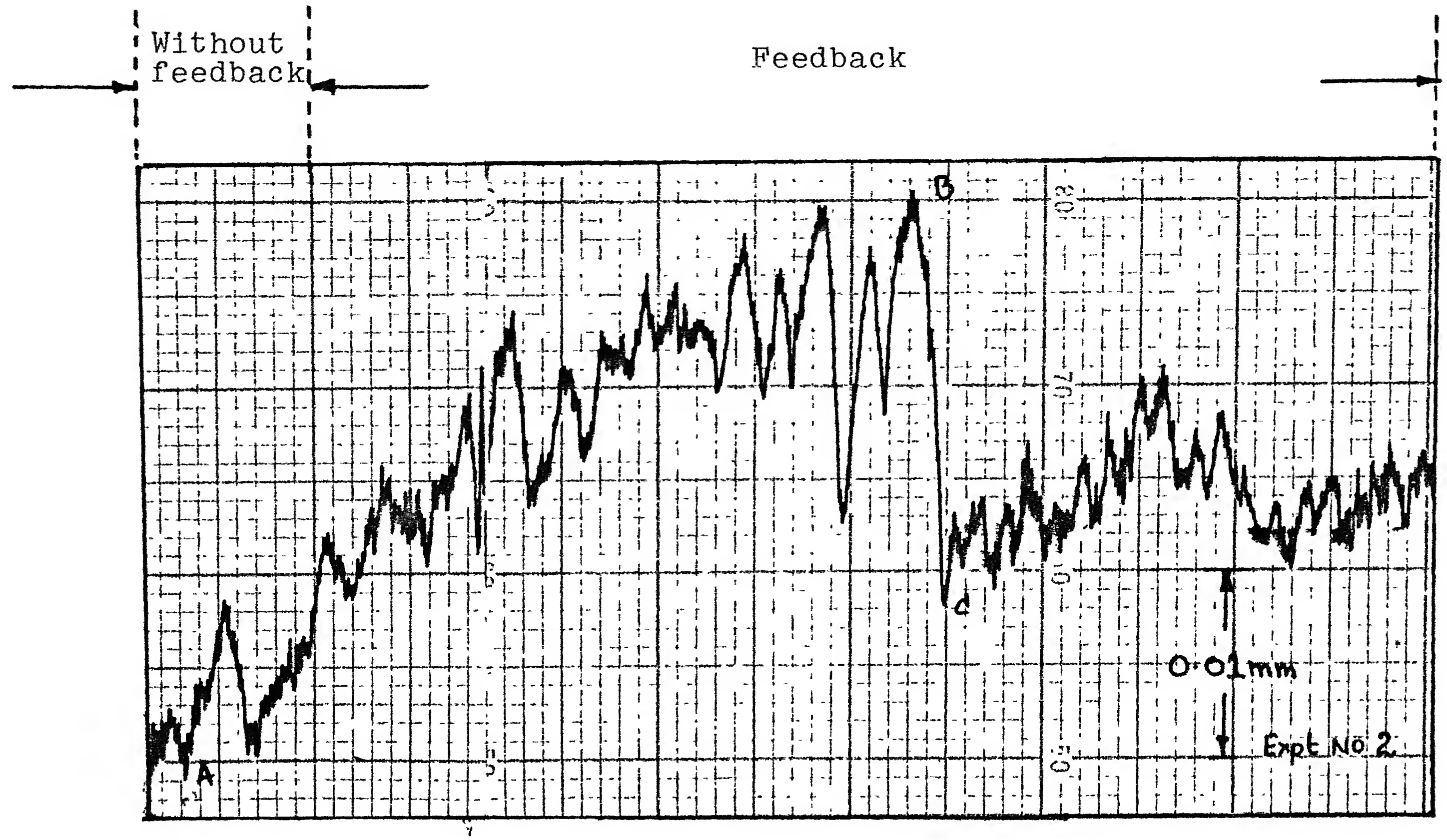

Fig. 3.2 : Optical Sensor Signal Pattern

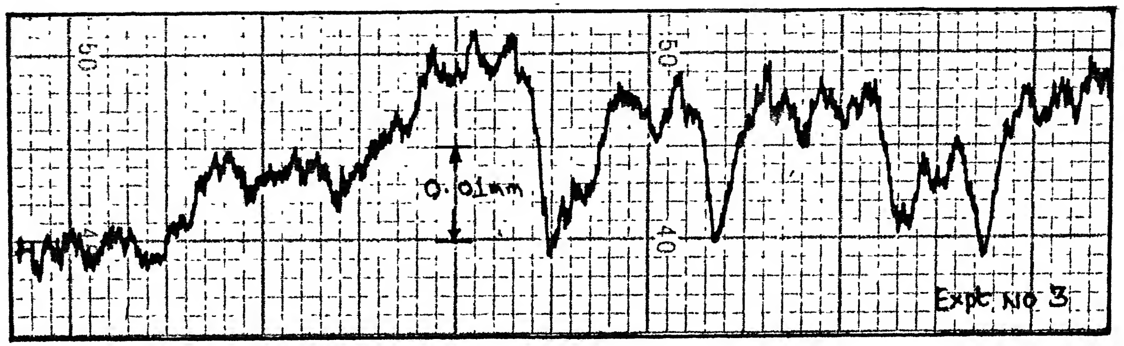

Fig. 3.3 : Optical Sensor Pattern with Continuous Feedback

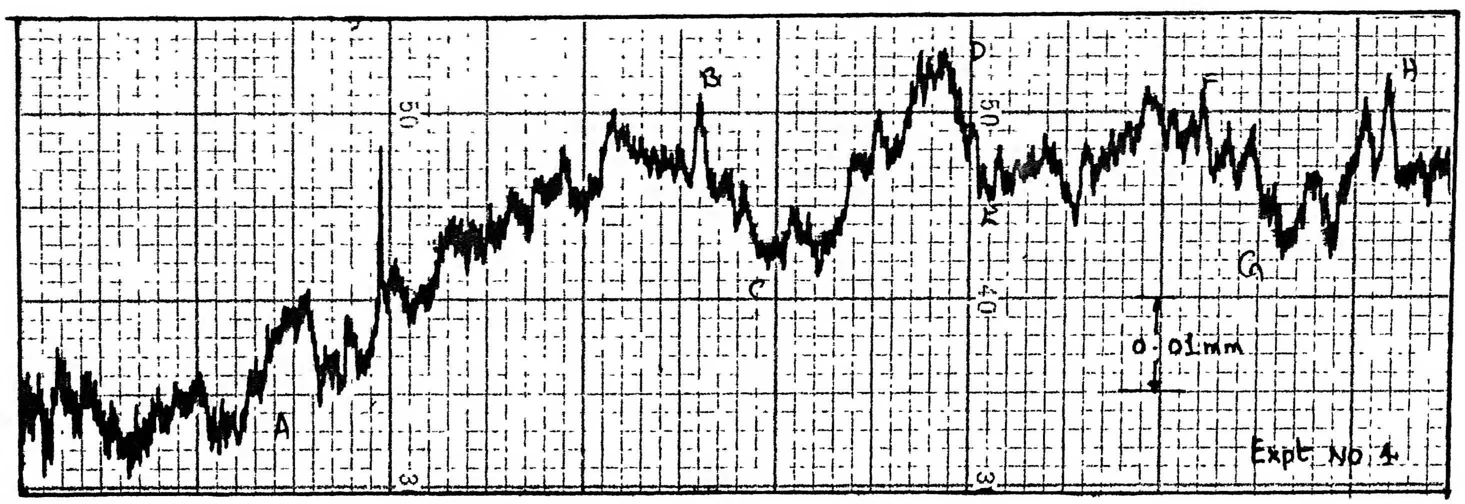

Fig. 3.4 : Optical Sensor Pattern with Continuous Feedback

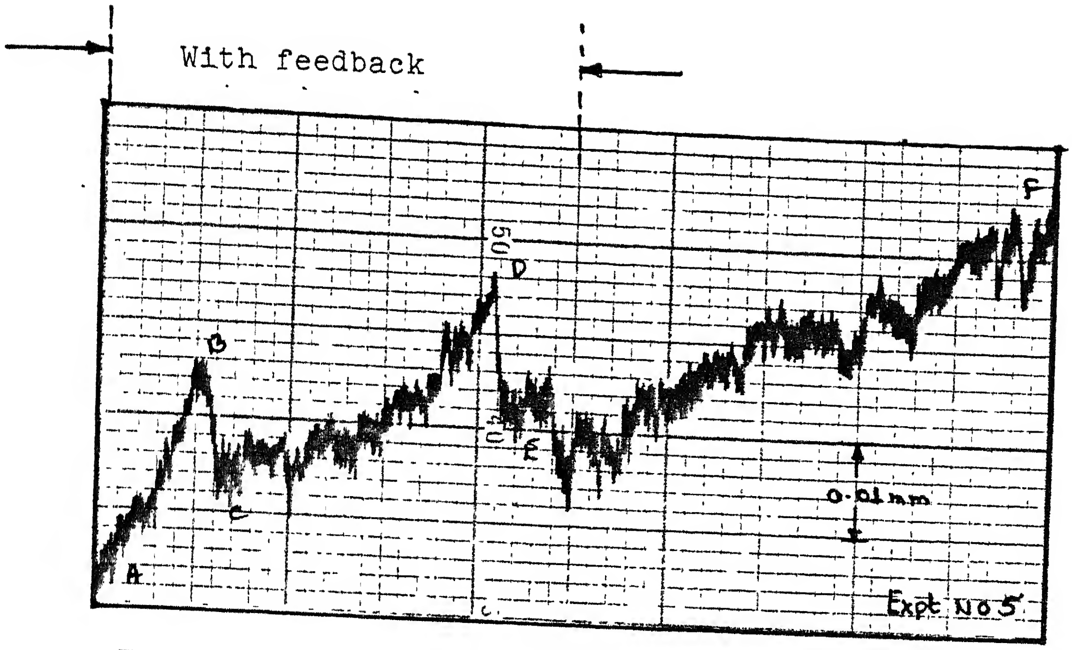

Fig. 3.5 : Optical Sensor Signal Pattern

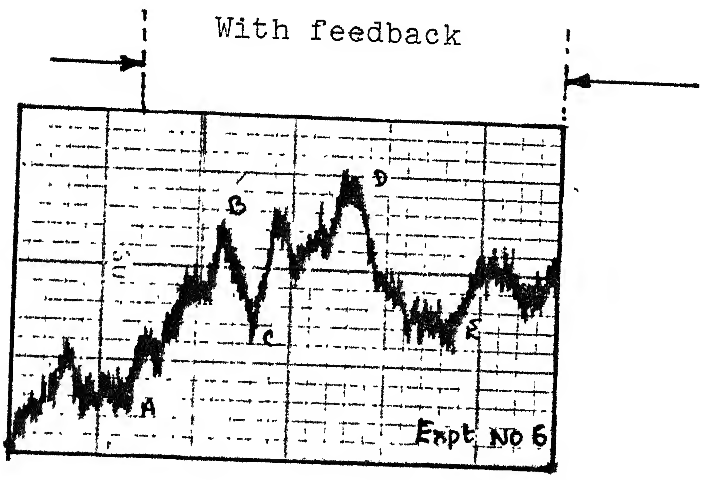

Fig. 3.6 : Optical Sensor Signal Pattern

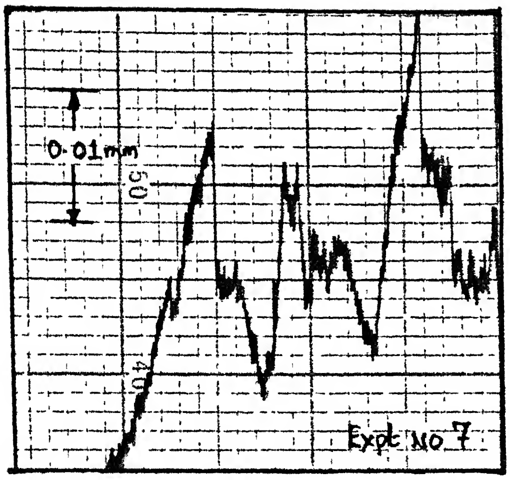

Fig. 3.7 : Optical Sensor Signal Pattern

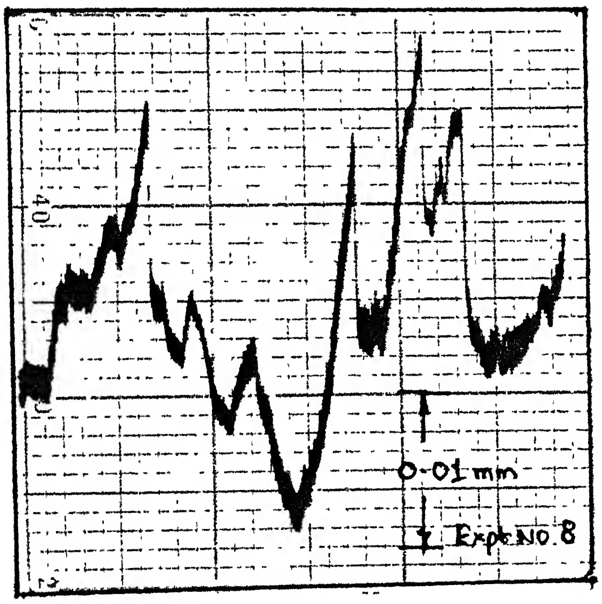

Fig. 3.8 : Optical Sensor Signal Pattern

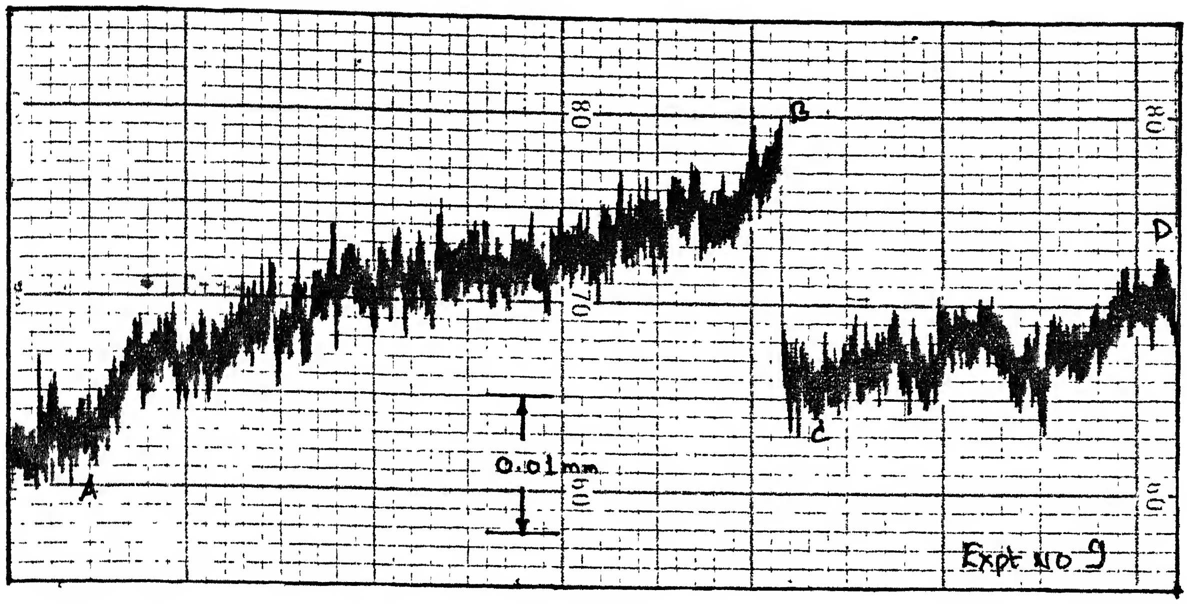

Fig.3.9a : Optical Sensor Signal Pattern

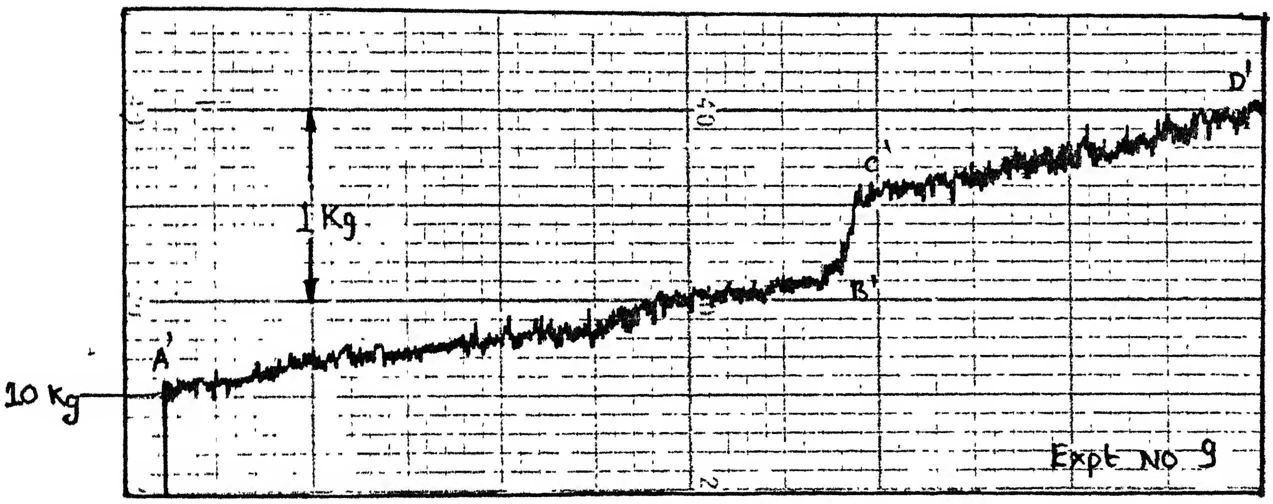

Fig. 3.9b : Dynamometer Signal Pattern for Feed Force Component

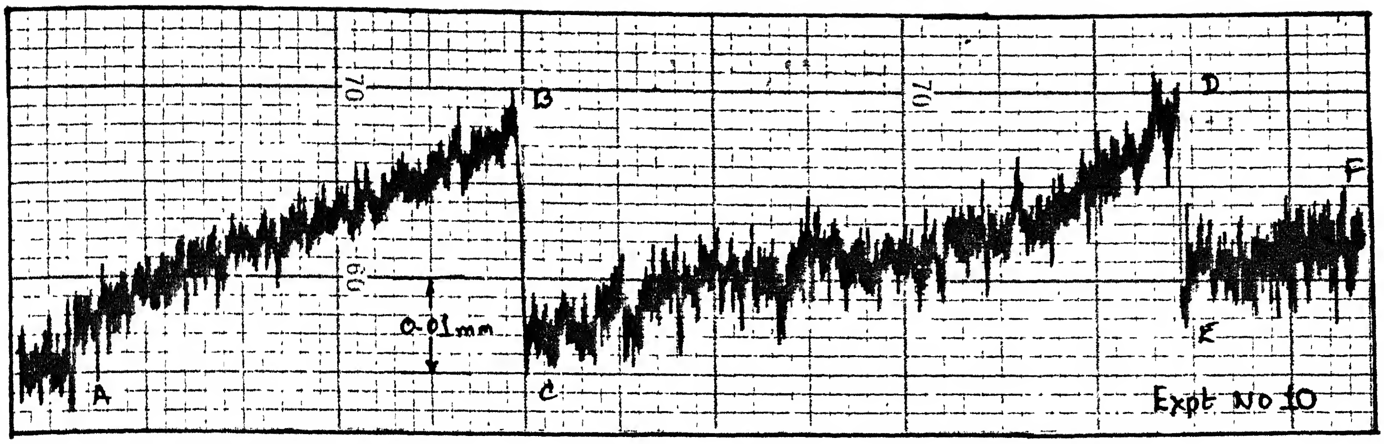

Fig. 3.o0a : Optical Sensor Signal Pattern

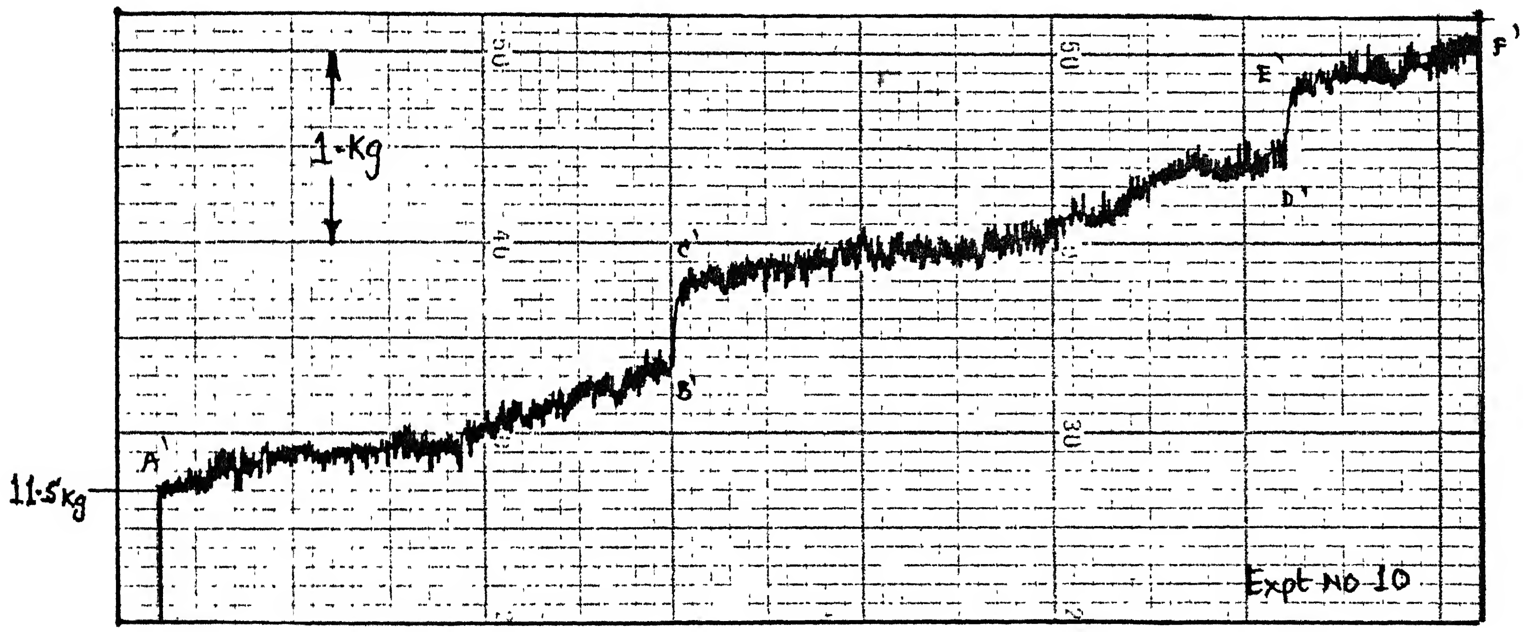

Fig. 3.10b : Dynamometer Signal Pattern for Feed Force Component

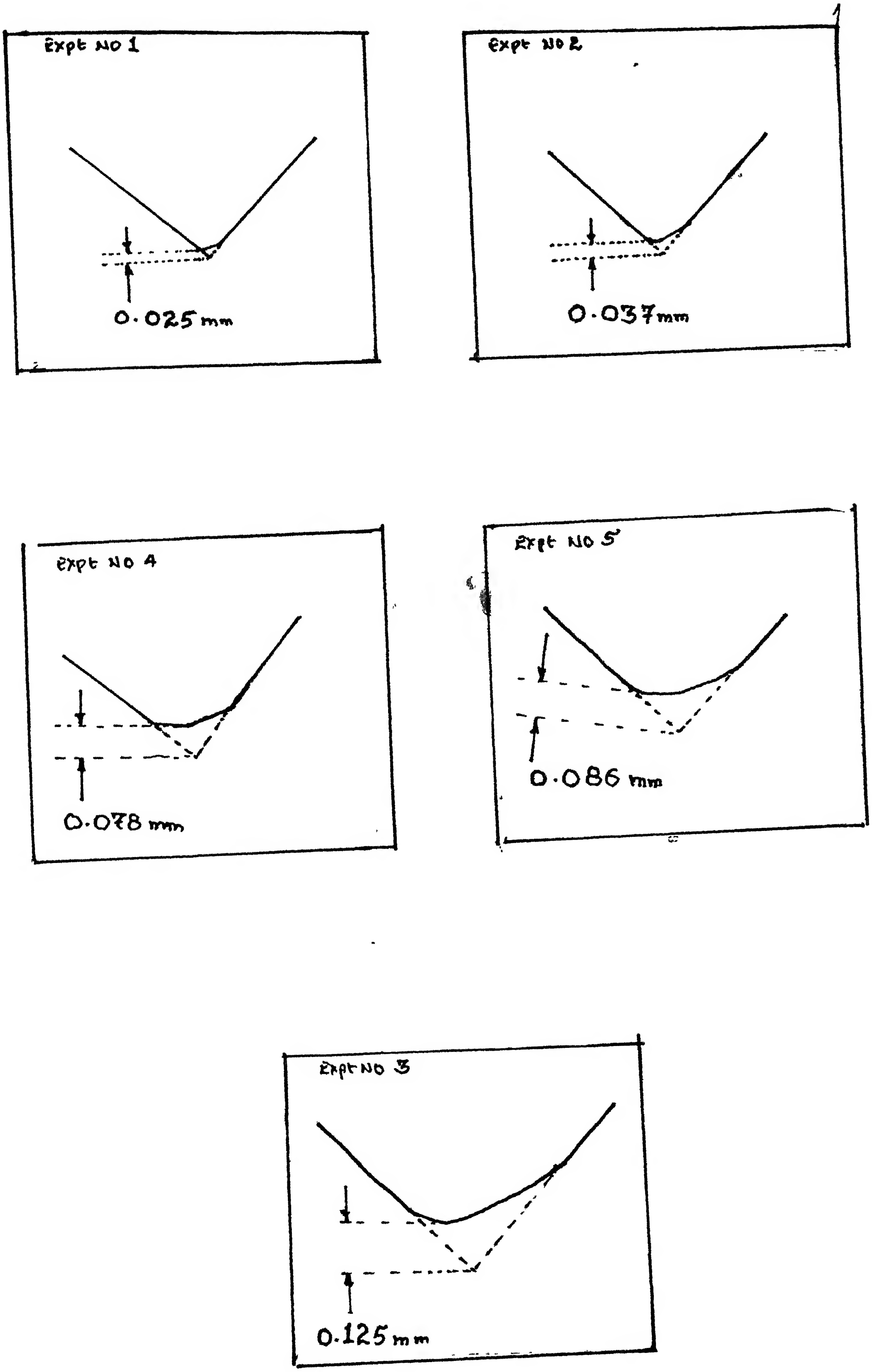

Fig. 3.11 : Shadowgraph Record for Measuring Tool Wear
Magnification: 50x

Table 3 : Comparison of Tool Wear Measurement

Expt.No.	Tool wear values from graphs	From shadow graph record
1	0.028 mm	0.025 mm
2	0.033 mm	0.037 mm
3	0.10 mm	0.125 mm
4	0.072 mm	0.078 mm
5	0.085 mm	0.086 mm

CHAPTER-4

CONCLUSIONS

4.1 Conclusions

An on-line control system has been designed and tested experimentally. The main objectives of on-line monitoring the tool wear and controlling the workpiece dimension have been fulfilled. The performance of the control system has been tested for certain range of cutting conditions. The principle of the present work, mainly, to reduce the effect of tool wear on the workpiece dimension by repositioning the tool, has been satisfied.

The following design objectives have been fulfilled:

(i) Designing of an accurate, reliable and sensitive sensor for monitoring tool wear in real time.

(ii) Design, fabrication and testing of tool actuator to reposition the tool.

(iii) Design of a feedback system to control the workpiece dimension during turning operations.

From the results obtained by the experiments, it can be concluded that the designed feedback control system is accurate enough to monitor the tool wear on-line and compensate for it.

A principal advantage of the control system is the simplicity of instrumentation. Instead of the conventional laser beam or a T.V. camera used for monitoring tool wear (as discussed in literature review), an optical sensor which has an ordinary bulb for illuminating the workpiece was used.

However the system has certain limitations:

(i) This system is applicable for only straight turning operations.

(ii) The system will not give sufficient and accurate results in case of severe machine tool chatter.

Apart from this, even when the tool wear is compensated, as discussed earlier, cutting forces increase . This affects tool life particularly while machining hard materials, to a considerable amount.

4.2 Scope for Future Work

The present work can be extended further. The controller is designed for a single input and single output system. But variation in cutting forces shows that the effect of tool wear will be on both workpiece as well as tool. Since cutting forces are direct functions of feed and depth of cut; a similar closed loop feedback control system of constant feed force constraint can be developed in addition to the existing system. This will lead to a multiinput, multioutput system. The effect of such a control over surface finish, material removal rate, dimensional accuracy and tool life can be studied.

Secondly, the workpiece deflection control (due to chatter) can also be incorporated with the compensation of tool wear. For this system a well defined logic has to be developed to identify tool chatter and tool wear separately (depending upon their dominations) and corresponding controls should be given by positioning the tool.

The above mentioned systems can be later clubbed to have a complete control over the disturbances in the machining process.

The application of the optical sensor developed for the present work has to be tested for ACO strategy. This will help in the complete study of process monitoring and control in a future oriented computer integrated manufacturing system.

Provision can be made to extend the suggested control systems of workpiece dimensions for machining processes other than turning.

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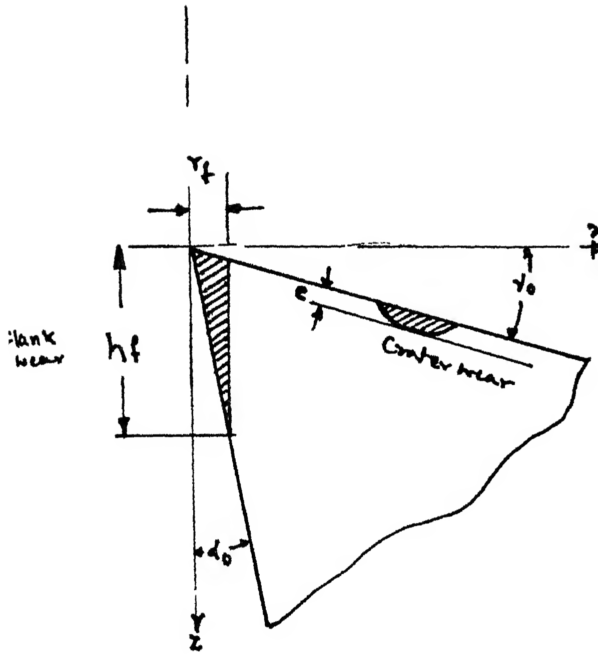
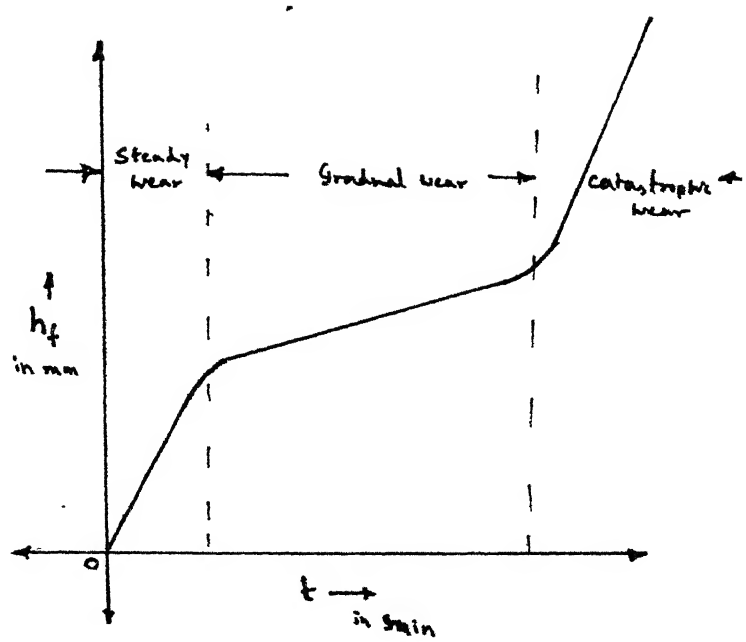
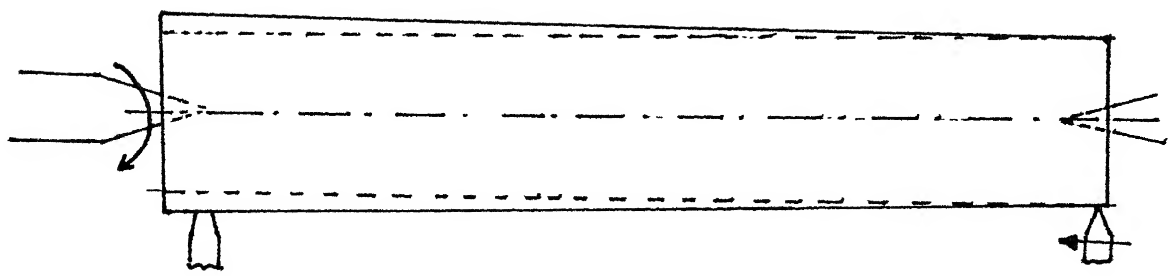


A-1(a) Geometry of wear forms



A-1(b) Three phase flank wear curve



A-1(c) The effect of flank wear on Dimension of workpiece.

great that while attempting to free the surfaces, separation takes place not along the interface but in one of the materials itself, transferring and removing materials often with the sliding member of the pair. Quantity of metal transferred is apparently proportional to the real area of contact, as well as on the hardness of the mating pair under prevalent environment.

Solid state diffusion occurs when atoms in a metallic crystal lattice move from a region of high atomic concentration to one of low concentration. This process is dependent on the existing temperature. In metal cutting, where intimate contact between the work and the tool materials occurs and high temperature exists diffusion can occur where atoms move from the tool material to the work material.

Figure A.1a shows the flank and crater wears on the tool. The flank wear is measured by the width of the flank wear land 'h_f' and the crater wear by the depth of crater. Fig. A-1b shows the three phase flank wear curve and the effect of flank wear on the dimension of the workpiece is shown in Fig.A-1C.

APPENDIX-II

On-Line Control

On-line control of metal-cutting process is a logical extension of the CNC systems. This on-line control is known as adaptive control. Adaptive control is basically a feedback system in which the operating parameters automatically adapt themselves to actual conditions of the process. The typical performance indices on which the adaptation takes place have been metal removal rate and cost per unit volume of metal removed.

Adaptive control system for machine tools can be classified as (a) Adaptive control optimisation (ACO), (b) Adaptive control constraint (ACC).

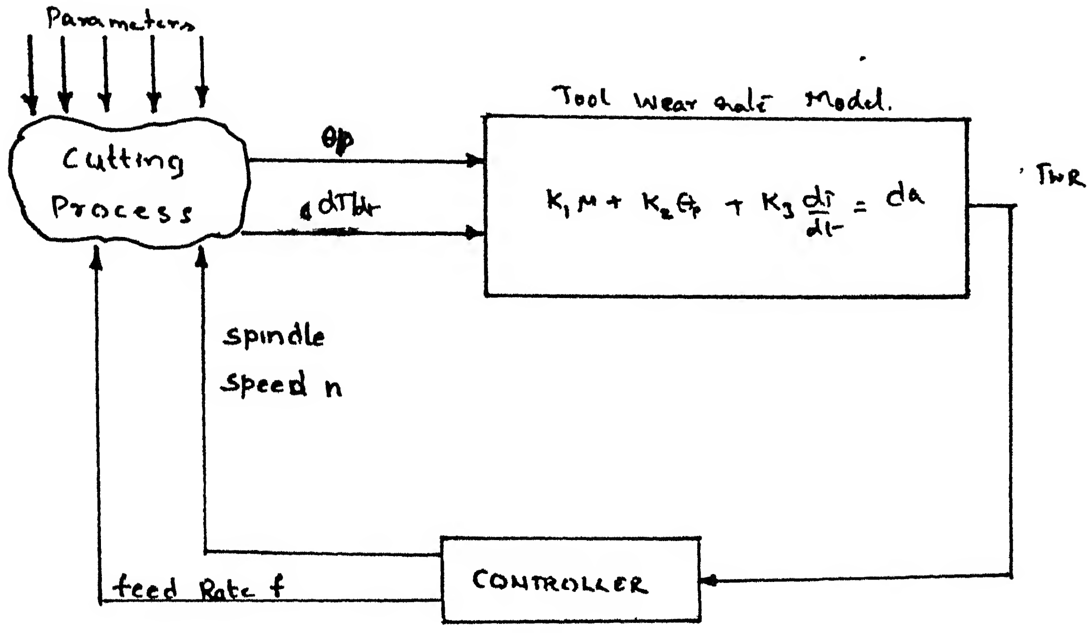
Figure A.2a shows the model for ACO in Fig. A.2b shows the model for ACC in a machining process.

In a typical ACO system the input of the adaptive controller is the data reduction system (DRS). This unit is fed by the on-line measurements as well as by the actual feed and speed and a set of constraints. The DRS produces two Signals : Tool wear rate (TWR)and metal removal rate (MRR) which are given by the following equation:

$$TWR = K_1\mu + K_2\theta + K_3 \frac{dT}{dt} \qquad A.1$$

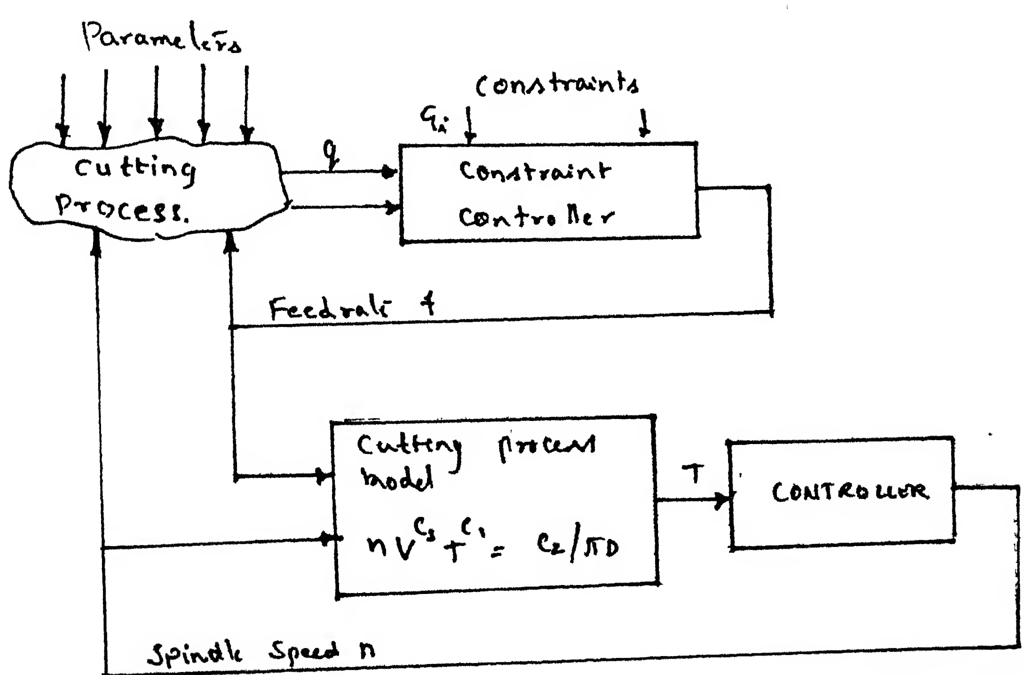
$$MRR = \mu = baf \qquad A.2$$

where θ is the tool temperature and dT/dt is the torque rate of change. K_1, K_2 and K_3 are constants prescribed by



K_1, K_2, K_3; constants

A-2(a) R.M. Centner and J.M. Idelson's ACO System



D: Tool diameter, c_1, c_2, c_3: constants, V: cutting Speed

A-2(b) An ACC System using Taylor's Tool life equation.

the tool and workpieces; b and a are width and depth of cut, respectively and f is the feed in mm/min.

The TWR and MRR signals are fed into a performance computer unit which calculates the performance index, or figure of merit Ø which is given by the equation:

$$\emptyset = \frac{MRR}{c_1 + (c_1\gamma + c_2\beta)\ (TWR)/w_o} \qquad A.3$$

where

c_1 = cost of machine and operator/unit time

c_2 = cost of tool and regrind/change

γ = tool changing time

w_o = terminal allowable width of flank wear

β = constant which establishes the performance criterion

β = 1, the criterion is cost per unit

β = 0, the criterion is production rate $0 \leq \beta \leq 1$

The calculated index Ø is fed into an optimization computer unit, which contains the strategy according to which the optimization is made. Thus the objective of this unit is to continually maintain the value of Ø at the highest possible value without causing any constraint violations.

APPENDIX-III

Appendix-IIIa

Microprocessor

A microprocessor is the control and processing unit of a small computer. Like all computer processors, a microprocessor can handle both arithmetic and logic data under the control of a program. To make a computer based on a microprocessor requires the addition of memory (for both the control programme and data), time-based logic and a set of input/output interface circuits to communicate with peripheral devices. The microprocessors provide inexpensive computer control to a variety of applications.

Appendix-IIIb

Microprocessor kit model used : DMS - MICRO FRIEND
ILC - V2

Hardware Features:

CPU	:	Intel 8085A CPU running at 3 MHz
Memory	:	16K monitor EPROM and 8K RAM with a battery backup for RAM
Key Board/Display	:	Key board consists of 24 dual function keys. They behave as command keys at power on, reset, or 'F' prompt and behave as hexadecimal number keys after any of the command key is pressed.

EPROM Programme	:	A 28 Pin Textool ZIF socket is provided for programming EPROMs
Parallel I/O	:	Parallel I/O in available through two 8255 chips
Timer	:	3 channel of 16 bit timer/ counters are provided by 8253
AD-DA	:	On board 8 bit analog to digital and digital to analog conversion is available using ADC 0809 (8 channels with 100 US conversion time per channel) and DAC 08 (single channel, with current settling time of 100 ns) ADC can measure voltage from 0 to 5V with tolerance of $\pm$ 19 mV.

APPENDIX-IIIC

ASSEMBLY LANGUAGE PROGRAM

LABEL	OP CODE	OPERAND	COMMENTS
9000	OE C8	MVI C, C8 H	MOVE IMMEDIATE DATA C8 TO C
9002	21 00 94	CXI H,9400	LOAD HL PAIR WITH IMMEDIATE DATA 9400
9005	AF	XRA	CLEAR ACCUMULATOR FOR SUMMING
9006	77	MOV M,A	MOVE A TO MEMORY
9007	47	MOV B,A	CLEAR B
9008	CD 00 92	CALL AT 9200	CALL SUBROUTINE AT ADDRESS 9200 WHICH READS ADC CH.NO.2 (OPTICAL FIBRE)
900B	86	ADD M	ADD MEMORY TO A
900C	D2 10 90	JNC 9010	IF NO CARRY, JUMP TO 9010 WITHOUT INCREMENTING B
900F	04	INR B	INCREMENT B; SAVE CARRY BIT
9010	77	MOV M, A	MOVE A TO MEMORY
9011	OD	DCR C	DECREMENT C
9012	C2 08 90	JNZ 9008	IF NOT ZERO JUMP TO 9008
9015	4F	MOV C,A	MOVE A TO C SO THAT THE SUM OF REFERENCE VOLTAGE TAKEN 200TIMES WILL BE STORED IN THE REGISTER PAIR B&C
9016	23	INX H	INCREMENT THE MEMORY TO 9401
9017	AF	XRA	CLEAR ACCUMULATOR
9018	77	MOV M,A	MOVE A TO MEMORY
9019	31 00 99	LXI SP, 9900	LOAD THE STAK POINTER WITH 9900
901C	CD 00 91	CALL AT 9100	CALL THE SUBROUTINE FOR SENSING THE ERROR (FEEDBACK) AND CALCULATING THE NO. OF STEPS THROUGH WHICH STEPPER HAS TO MOVED
901F	E5	PUSH H	PUSH H&L ONTO STACK
9020	21 0095	EXI H, 9500	LOAD HL PAIR WITH 9500

LABEL	OPCODE	OPERAND	COMMENTS
9023	3E 80	MVI, 80	MOVE IMMEDIATELY 80H TO A
9025	D3 OB	OUT, OB	INITIATIVE THE OUTPUT PORT
9027	7E	MOV A, M	MOVE MEMORY TO A
9028	D3 08	OUT, 08	OUTPUT THE DATA TO THE PORT
902A	CD 00 93	CALL, 9300	CALL TIME DELAY ROUTINE AT 9300
902D	E1	POP H	POP HL FROM SP
902E	1D	DCR E	DECREMENT E
902F	C2 35 90	JNZ, 9035	IF NOT ZERO JUMP TO 9035
9032	CD 0091	CALL, 9100	CALL AT 9100
9035	E5	PUSH H	PUSH HL ONTO STACK
9036	21 01 95	LXI H, 9501	LOAD HL WITH 9501
9039	3E 80	MVI, 80	
903B	D3 05	OUT, OB	
903D	7E	MOV A, M	
903E	D3 08	OUT, 08	
9040	CD 0093	CALL DELAY	
9043	EI	POP H	POP HL FROM SP
9044	1D	DCR E	DECREMENT E
9045	C2 4B 90	JNZ, 904B	IF NOT ZERO JUMP TO 904B
9048	CD 0091	CALL, 9100	CALL AT 9100
904B	E5	PUSH H	PUSH HL ONTO STACK
904C	21 02 95	LXI H, 9502	LOAD HL WITH 9502
904F	3E 80	MVI, 80	
9051	D3 OB	OUT, OB	
9053	7E	MOV A, M	

LABEL	OP CODE	OPERAND	COMMENTS
9054	D3 08	OUT 08	
9056	CD 0093	CALL, 9300	CALL DELAY
9050	E1	POP H	POP HL FROM SP
905A	1D	DCR E	DECREMENT E
905B	C2 6190	JNZ 9061	IF NOT ZERO JUMP TO 9061
905E	CD 00 91	CALL, 9100	CALL AT 9100
9061	E5	PUSH H	PUSH HL ONTO SP
9062	21 03 95	LXI H, 9503	LOAD HL WITH 9503
9065	3E 80	MVI, 80	
9067	D30B	OUT, OB	
9069	7E	MOV, A, M	
906A	D3 08	OUT 08	
906C	CD 00 93	CALL, 9300	CALL DELAY
906F	E1	POP H	POP HL FROM SP
9070	1D	DCR E	DECREMENT E
9071	C2 1F 90	JNZ 901F	IF NOT ZERO JUMP TO 901F
9074	C3 1C 90	JMP 901C	JUMP TO 901C
			SUBROUTINES: FEEDBACK,ERROR AND NO.OF STEPS
9100	1E C8	MVI E, C8	MOVE IMMEDIATE C8H to 8
9102	AF	XRA	CLEAR A
9103	57	MOV D, A	CLEAR D
9104	CD 00 92	CALL, 9200	CALL AT ADDRESS 9200 FOR ADC CH. NO.2
9107	86	ADD ID	ADD MEMORY TO 4
9108	D2 OD 91	JNC 910C	IF NO CARRY JUMP TO 910d
910B	14	INR D	SAVE THE CARRY BIT
910C	77	MOV M, A	MOVE A TO MEMORY

LABEL	OP CODE	OPERAND	COMMENTS
910D	1D	DCR E	DECREMENT E
910E	C2 0491	JNZ 9104	IF NOT ZERO JUMP TO 9104
9111	5F	MOV E, A	MOVE A TO E
			SENSED VOLTAGE (FEED BACK) IS STORED IN REGISTER PAIRDE
9112	AF	XRA	CLEAR A
9113	77	MOV M, A	MOVE A TO MEMORY
9114	7B	MOV A, E	MOVE E TO A
9115	91	SUB C	SUBTRACT C FROM A
9116	5F	MOV E,A	MOVE A TO E
9117	7A	MOV A,D	MOVE D TO A
9118	98	SBB B	SUBTRACT B FROM A WITH BARROW
9119	DA 00 91	JC, 9100	IF THE CARRY IS SET; I.E. IF THE VALUE OF THE ERROR IS NEGATIVE JUMP TO 9100
911C	57	MOV D,A	IF NOT MOVE A TO D
			SO THAT THE NET ERROR FROM FEEDBACK WHICH IS +VE WILL BE STORED IN THE REGISTER PAIR DE
911D	E5	PUSH H	PUSH HC ON SP
911E	2E 00	MVI L, 00	MOVE IMMEDIATE 00 to L
9120	2C	INR L	INCREMENT L
9121	7B	MOVE A, E	MOVE E TO A
9122	D6 90	SUI, 90	SUBTRACT IMMEDIATE DATA 90 FROM A
9124	5F	MOV E,A	MOVE A TO E
9125	7A	MOV A,D	MOVE D TO A
9126	DE 01	SBI, 01	SUBTRACT 01 FROM A WITH BARROW
9128	D2 2E 91	JNC, 912E	IF NO CARRY JUMP TO 912E

LABEL	OPCODE	OPERAND	COMMENTS
912B	C3 32 91	JMP, 9132	JUMP IF CARRY TO 9132
912E	57	MOV D, A	MOVE A TO D
912F	C3 2091	JUMP, 9120	JUMP to 9120
9132	2D	DCR L	DECREMENT L
9133	CA 3991	JZ, 9139	IF ZERO JUMP TO 9139
9136	C3 3D 91	JMP, 913D	JUMP TO 913D
9139	E1	POP H	POP HL FROM SP
913A	C3 00 91	JMP, 9100	JUMP TO 9100
913D	5D	MOV E, L	MOVE L TO E
913E	E1	POP H	POP HL FROM SP
913F	C9	RET	RETURN FROM ROUTINE
			SUBROUTINE ADC
9200	3E 8A	MVI. A, 8A	CONTROL WORD IN H
9202	D3 13	OUT 13	OUT TO CONTROL PORT2 DEFINE PORT B ON INPUT PORT C LOWER HALF INPUT UPPER HALF OUTPUT
9204	3E 08	MVI A, 08	OUTPUT OF ADC DISABLED AS OUTPUT ENABLE IS CONNE-CTED TO P2C3
9206	D3 12	OUT 12	OUT TO PORT P2C
9208	3E 80	MVI A,80	CONTROL WORD IN A
920A	D3 OB	OUT OB	OUT TO CONTROL PORT 1
920d	3E 2F	MVI A, 2FH	STAND BY WORD FOR ZIF
920E	D3 OA	OUT, OA	OUT TO PORT P1C
9200	3E 02	MVI A, 02	ADDRESS FOR CHANNEL No.2
9212	D3 08	OUT, 08	OUT TO PORT P1A P1A0, P1A1, P1A2 SELECT THE CHANNEL ADDRESS
9204	3E OE	MVI A, OE	

LABEL	OPCODE	OPERAND	COMMENTS
9216	D3 12	OUT, 12	OUT TO PORT P2d TO MAKE P2C1 (START) AND P2C2 (ACE) HIGH THIS WILL LATCH THE RELATED ADDRESS AND START CONVERSION
9218	3E OC	MVI A, OC	
921A	D3 12	OUT 12	OUT TO PORT P2C TO MAKE P2C1 (START) PULSE LOW AGAIN
921C WT	DB 12	IN 12	READ PORT P2C TO LOOK FOR END OF CONVERSION SIGNAL
921E	E6 40	ANI 40	GET BIT P2C6 (EOC)
9200	CA 1C 92	JZ, WT	WAIT TILL P2C6 = 1
9223	AF	XRA	CLEAR ACCUMILATOR
9224	D 312	OUT 12	OUT TO PORT P2C TO MAKE ALL LINES LOW. THIS ALSO ENABLES THE OUTPUT FROM ADC
9266	DB 11	IN 11	READ PORT P2B WHICH IS OUTPUT OF ADC (P2BO TO P2B7)
9228	C9	RET	RETURN FROM SUBROUTINE

SUBROUTINE DELAY

LABEL	OPCODE	OPERAND	COMMENTS
9300	E5	PUSH H	PUSH HL PAIR ONTO SP
9301	26 10	MVI H, 10	MOVE IMMEDIATELY 10 to H
9303	2E FF	MVI L, FF	MOVE IMMEDIATELY FF TO L
9305	2D	DCR L	DECREMENT L
9306	C2 05 93	JNZ, 9305	IF NOT ZERO JUMP TO 9305
9309	25	DCR H	DECREMENT H
930A	C2 03 93	JNZ 9303	IF NOT ZERO JUMP TO 9303

LABEL	OPCODE	OPERAND	COMMENTS
930D	E1	POP H	POP HL FROM THE SP
930E	C9	RET	RETURN FROM THE SUBROUTINE
			DATA FOR STEPPER MOTOR
9500	05		0000 0101
9501	06		0000 0110
9502	0A		0000 1010
9503	09		0000 1001

APPENDIX-IV

Type of centre lathe	:	M6D2
Centre height	:	165 mm
Centre distance	:	1000 mm
Swing over bed	:	330 mm
Swing over cross slide	:	120 mm
Spindle speeds	:	48, 72 to 1000 rpm
		(1 HP motor at 1440 rpm).